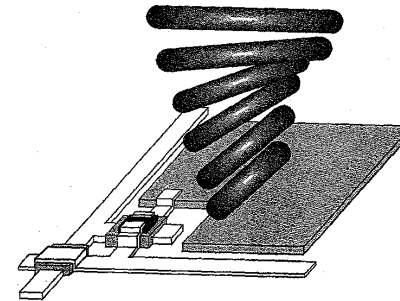


COLOR TFT LIQUID CRYSTAL DISPLAYS

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FOREWORD

Currently we are in the midst of a technological revolution in displays. For more than fifty years, complex information displays, including television screens, have been dominated by one outstanding device, the cathode ray tube (CRT). While the CRT has continually evolved to larger sizes, higher performance (most notably with the addition of color in the '50s), and lower cost, by its very nature as a vacuum tube it is a heavy and cumbersome device. The tremendous progress in microelectronics which has made portable systems feasible, especially portable televisions and portable computers, has created the market need for a thin and light low-powered device to replace the CRT. While many candidate technologies have emerged and contended to meet this market, it is possible now to declare a winner, and that winner is the active matrix liquid crystal display. Ultimately there may be additional challenges to undermine further the CRT's dominance, such as large plasma panels for TV-on-the-wall, but they have not yet demonstrated economic success. Chapter 1 of this book discusses the role of the active matrix LCD in current and future markets, including computers, interactive TV and multimedia applications. Sales of active matrix LCDs are approaching in value the sales of CRTs, with much higher growth rates. This is the fact which justifies the use of the term revolution.

As many revolutions, which only seem to be sudden, the seeds were planted many years ago. In the late 1960s, when liquid crystal displays were in their infancy, it was recognized that they carried the potential for creating flat television screens, or TV-on-the-wall, provided that a practical

means for electrically addressing a large number of cells could be achieved. By 1971, B. J. Lechner and others at the RCA Laboratories had catalogued a whole list of possible approaches to this addressing problem, one of which was to have an array of thin film transistors (TFTs, another RCA invention) such that the voltage on each liquid crystal picture element could be individually controlled. Until now, relatively little material has been available to the non-specialist that would provide a basis for understanding the light-switching function of the liquid crystal, and the electrical addressing function of the TFT array. Chapter 2 provides this background information.

Unfortunately, at the time the idea of making a TFT array large enough to be suitable for a TV picture, essentially defect free, was not considered practical and was not pursued by RCA. At Westinghouse, however, T. P. Brody came to a different conclusion. He judged that TFT-controlled displays were a practical possibility and set out to make prototypes. By 1974, Brody and his group had made TFT-controlled electroluminescent displays, as well as the first TFT-controlled liquid crystal displays, by that time using the 90° twisted nematic (TN) liquid crystal cell, which has been the cell of choice ever since.

It took another ten years for the first TFT/LC displays to appear in commercial products, most notable in small pocket TV sets from Japan. By that time new materials had been introduced for the thin film transistor arrays, in competition with the cadmium selenide used in the TFTs developed by Brody and coworkers. The new materials were polysilicon and amorphous silicon. By the end of the 1980s there had developed an industry consensus that for economical high-volume production, amorphous silicon was the material of

choice, partly because the technology for producing uniform, high quality films on large substrates had already been developed by the solar cell industry. The manufacturing technology that has evolved to serve the display industry is the subject of Chapter 3.

The technology was ready, but the pocket TV market was not large enough to drive the level of investment needed to challenge the CRT. By 1989 it was clear that there was such a market, and it was the portable personal computer market. Personal computer users were accustomed to using color CRTs, and it was felt that in the end they would insist on displays for their portable computers which could match CRT performance. Since CRTs could not be used, relative cost was not an issue. Initially, TFT/LC flat panels cost five times what a CRT cost, but this was irrelevant; they provided a new platform for taking work anywhere.

We have now come to the point where just about everyone is familiar with the marketing terms "active matrix LC display", and it is widely understood that this means very high image quality (as well as somewhat higher cost than competitive supertwisted nematic (STN) passive matrix displays).

This book was compiled for the benefit of those who would like to know more about what is behind the words "active matrix" or "color TFT" liquid crystal displays. It was written by a group of Japanese authors and translated under the auspices of SEMI. It should serve well as a valuable introduction to a fascinating and rapidly evolving technological revolution, the impact of which is only beginning to emerge.

December 6, 1995

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INTRODUCTION

This book represents the work of a committee formed in Japan under the auspices of the Semiconductor Equipment and Materials International (SEMI) organization in Tokyo known as SEMI/Japan. The committee, called the SEMI Standards FPD Technology Group, was chaired by Mr. Teruhiko Yamazaki of Mitsubishi Corporation and consisted of 19 members. Mr. Yamazaki also served as chair of the Flat Panel Display Standards Division in the Japan region of the SEMI International Standards Program. The committee was motivated to produce this book to fill the need for a comprehensive source of information on color TFT liquid crystal display technology in a single publication. Individual Chapters were written by key committee members having expertise in specific technical areas. The final result is a book that is both a primer for the individual interested in an overview of TFT LCD technology as well as a reference volume for those well versed, in perhaps, only certain aspects of this burgeoning field.

The book was first published in the Japanese language and distributed in a limited way in Japan in early 1995. Recognizing a need to make the work of the Japanese committee available to a wider audience, the SEMI international office in Mountain View, California undertook the task of translation and publication. O'Mara and Associates in Palo Alto, California was commissioned to perform the translation and technical editing of the final copy. The lead translator for this work was Mr. Shunsuke Obinata. Every effort was made to remain faithful to the original work. The book relies heavily on visuals to explain display operating

principles and therefore precise extraction of all graphics from a single optical disk containing the Japanese edition was required. This work was performed by Proteus Typography in Palo Alto, California.

The final result is a book that leads the reader easily into the complexities of flat panel display technology without unnecessary detail. While materials issues are highlighted, virtually all elements of the technology are discussed and relationships are explained. The Japan committee, in their preface to the original edition, expressed the hope that their work would be valuable in explaining fundamental principles and perhaps assist in the conception of new ideas in liquid crystal display technology. We feel their goal has been achieved.

SEMI
Mountain View, CA 94043
December 31, 1995

PREFACE

The liquid crystal, discovered by T. Reinitzer in 1888, was first developed by N. Heilmair at RCA Corporation in 1968. After over 100 years since its initial discovery, the liquid crystal has become ubiquitous in our daily lives. In particular, the thin-film transistor LCD, an offspring of advanced semiconductor production technology, has made remarkable gains in recent years. The liquid crystal is no longer a means for developing display products; because of its wide application potential, it is likely to impact virtually every facet of our lives as we move into the 21st century. It is now clear that the field of liquid crystals will become an extensive industry on its own. These trends have led to a rapid increase in the number of researchers and engineers involved in liquid crystal technology or LC business activity.

The SEMI Standard FPD Technology Group undertook the publication of this book as an introduction to the liquid crystal for those who wish to familiarize themselves with the field from ground up. The book, centered on a discussion of fundamentals, covers the principles of the liquid crystal, manufacturing methods, and the properties of the materials of which liquid crystals are composed.

In liquid crystal technology, an important objective is to develop and manufacture products that fully exploit the properties of constituent materials. Workers involved in the various aspects of the liquid crystal field, including research and production, need to have an accurate understanding of many subjects, including the materials that go into a product, underlying processes, drive methods, and operating principles. This book attempts to expound the

field in a manner that the beginner will find easy to understand by answering basic questions, such as why a given product operates in a certain way and what are the reasons for using particular materials for making that product. The book is also intended as a review for busy managers and engineers working on the forefront of the technology. It is hoped that the book will be a valuable aid in explaining what is taken for granted from the perspective of fundamental principles and thus will help in conceiving new ideas.

If some readers find that this book has helped them discover a new starting point, the authors and editors of this book would feel that their dream has been amply fulfilled.

This book was completed through the efforts of many members of the SEMI staff and of the FPD Technology Group who devoted many hours out of their busy schedules. We hope that the book will be a handy desktop companion for those who are engaged in all aspects of liquid crystal technology.

October 1, 1994

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SEMI STANDARD ACTIVITY

The SEMI Standard Activity was initiated virtually coincident with the establishment of Semiconductor Equipment and Materials International (SEMI) in 1970. Currently, 3,500 members belong to the three Standard Committees, located in Japan, North America, and Europe, and are carrying out various standards development activities relating to the semiconductor transistor, including the AMLCD.

The role and objective of the SEMI Standard Activity Group is defined in the SEMI Standard Committee charter as follows:

Role: "The SEMI Standard Activity Group was established by the SEMI Board of Directors in order to develop international standards on equipment and materials related to the fabrication of semiconductors. The Group is intended to play a supplementary role in solving technical problems by providing a forum for the exchange of data and information between users and suppliers."

Objective: "The objectives of the SEMI Standard Group are to disseminate, worldwide, the definitions and product specifications that are developed by mutual agreement between users and suppliers and to define up-to-date operating procedures in both quality and capability aspects, thereby helping to promote the growth of the semiconductor industry. Toward this end, the SEMI Standard Group takes measures to ensure participation in the standards development process by representatives from as many countries as possible, including the representatives of organizations that are engaged in the field of semiconductor technology."

Another important feature of the SEMI Standard Activity Group is the "Democratic Procedures and Their Assurance."

Democratic procedures: The freedom of participation, the freedom of speech, and the freedom of balloting are guaranteed. In particular, the freedom to voice dissenting opinions and the freedom to vote in opposition are specifically guaranteed. Further, no organizations within the SEMI Standard Activity Group (committees, working groups, etc.) may suppress opposing views or opinions."

Equality of procedures: "The equality of procedures in the three regions, Japan, North America, and Europe, is guaranteed: members are free to participate, speak, and vote in any of the three regions."

Grievance procedure: "Any member having a grievance against a resolution adopted by the Committee is guaranteed an opportunity to submit his or her opinion to, or speak at, any of the regional standard committees, the international standard committee, and, ultimately, the SEMI Board of Directors.

Another significant feature of the SEMI Standard Activity Group with regard to day-to-day activity is patents and safety. Basically, it is provided that "patent-related items are not subject to SEMI standardization." If a problem arises with a patent after a standard is established (an incident that occurred in Japan), consultation is conducted with the holder of the patent. As for safety, in the case of a conflict, the most widely defined law or regulation is referenced because the three regions are subject to differing statutory regulations. This task is handled by SEMI legal counsel and safety technology advisors. For example, an aspect of LCD technology not subject to Japanese

governmental safety regulations may be subject to European or American governmental safety regulations. The International Standards Committee has the responsibility for conducting the final review on patent and safety-related issues. Other final reviews are performed by regional standards committees.

In terms of specific tasks, the various committees of SEMI are working on the standardization of terminology, specifications, and test methods. As one of these organizations, currently the Flat Panel Display (FPD) Technology Group, is addressing various issues related to the liquid crystal. The Group contains a substrate committee, a mask committee, an equipment committee, and a color filter committee.

Due to space limitations, details of how these committees are organized and the projects they are working on must be omitted. Interested parties might wish to contact the SEMI Japanese Region Standards Office (03-3222-5755) for further information.

SEMI Japan
Standards Office

COMMENTS ON THE EDITING PROCESS

In planning the publication of this document, we laid out the book with the motto of "From the Basic Fundamentals to the Practical Use of LC." Our goal was to use graphics liberally, so that the reader could quickly understand the content of a given section by looking at the figures presented in that section. Therefore, editing this book involved creating numerous figures, so as to provide as much visual presentation of material throughout the book as possible. For example, when discussing the propagation of light into TN and STN liquid crystals, specialists in the field normally express ideas in terms of the Gooch-Tarry equation. By contrast, in this book we purposely used graphics to convey the information to the reader. The apparent simplicity of visual information, however, conceals the fact that presenting information graphically requires a considerably larger amount of accurate information than rendering the same content textually. Further, no adequate treatment can be found in existing teaching materials of topics such as the rotation of light in liquid crystals and the composition of TFT elements. Therefore, in this book we sought to provide a scientific discussion, intended for beginners who are engaged in research or production, of the fundamental questions in optics, such as why the twist angle of a TN liquid crystal agrees with the rotation of the polarization axis. In addition, from developmental historical perspectives and from a practical standpoint, such as in terms of production yields, the book also answers the question of why dual gates and aluminum gates are necessary. Therefore, the

effort has been made to organize this book so that experts can employ it when teaching beginners. As for how beginners might use this book, we sincerely hope that they will consider it the bible on liquid crystal technology.

In writing and editing this book, committee members responsible for drafting various sections prepared manuscripts in DOS text format on the assumption that their output would be edited (desktop-published) on a Macintosh LC475 platform (20MB RAM, 160MB hard disk). Subsequently, all editing operations were performed using just one Macintosh computer.

The following software packages were used: Solo Writer for word-processing, Mac Draw Pro for creating figures, and Ofoto for generating image data. The document file was created by cutting and pasting the various items to a Pagemaker 4.5J file. A Canon scanner IX-4015 was used for reading image data. A Canon Laser Shot A404E was used for printing.

Compared to Illustrator, Draw software requires modifications of drawn graphs during cutting and pasting. However, when used in combination with the LISP III mode of the Laser Shot, this software is able to maintain a high level of resolution. Although artwork manuscripts produced on a Laser Shot are not on a par with those created on a PostScript printer, the editors of this book are favorably impressed with the capabilities of the Laser Shot A404E printer.

October 1, 1994

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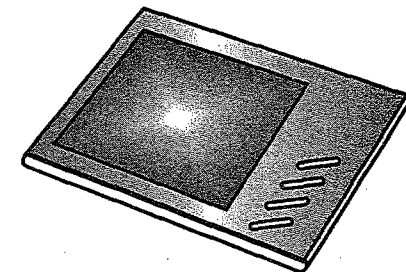
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CHAPTER 1

THE WORLD OF COLOR TFT LIQUID CRYSTAL DISPLAYS

1.1 CURRENT STATUS OF COLOR TFT LCDS

1.1.1 A Wealth of Applications

Color TFT LCDs are turning up everywhere these days. The color TFT display, a light, slender display, with a beautiful image that does not tire the eyes even when viewed for hours at a time, is finding its way into many products, even in demanding environments, like the dashboard of a car. Because the color TFT display is an LCD (liquid crystal display) panel incorporating thin film transistors, it can reproduce a wider range of colors than can competing technologies. The color TFT shows extremely uniform brightness, with no color degradation or distortion, even in the corners of the screen.

As shown in Figure 1.1, specific applications with significant growth potential for the color TFT, include portable computers, desktop computers, audio visual equipment, automotive navigation systems, game



FIGURE 1.1 Applications of the color TFT display

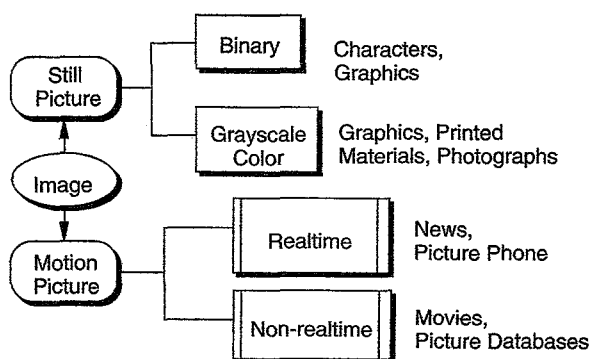
and simulation machines, and intelligent terminals. For example, in aircraft, color TFTs are installed as intelligent terminals in the cockpit. Above the passenger seats, color TFT displays may be found as information and entertainment screens. In marine applications, the color TFT can be used in fish finders and navigation devices. As audio visual equipment, color TFT-based TV sets and video machines are already a common sight in train stations and other public facilities in Japan. For the home, personal, pocket-size color TFT TVs are being developed. For the office, personal computers equipped with these new displays have begun to appear.

The increasing popularity of the color TFT is fueled by the growth of picture and symbol-based information display systems (graphical user interface - GUI) that permit intuitive man-machine interactions, rather than man-machine communications based exclusively on numbers and characters. The spread of personal computers and word processors into the home as well as the office, is also generating greater use of the color TFT.

Increases in the capabilities of the computer account, in large part, for the many ways in which information can be processed and presented so that it is easy to view and understand. Together with advances in communication, software, semiconductor, and computer technologies, the color TFT will continue to play an important role in the social environment of the future.

1.1.2 Beautiful picture quality

The goal of the color TFT is to bring into the realm of practical use electronic displays on a par with the color photograph, a mature technology. When it has attained a resolu-



FIGURES 1.2 Still and animated displays

tion comparable to that of a color photo, the color TFT can begin to make inroads, as a means of information transmission, in still picture systems. In the field of digital technology, which is advancing at a breathtaking pace, techniques for converting movie films to high-definition color digital imagery are being developed.

Figure 1.2 shows various levels of information content in images. There are two types of images: still and animated. For each of these, the binary display, in which the elements comprising a screen are displayed in bright and dark dots, is the simplest unit of image formation. Beyond this, grayscale output, which contains intermediate tones that can vary the brightness of elements, is capable of producing images in a wide range of shades. The addition of RGB (red, green, and blue) to this capability produces vibrant colors. Television produces the sensation of movement by creating still pictures at a rate of 30 to 60 frames per second. The sequence of images necessary to achieve the effect of motion must be displayed at a speed at which

the eye cannot distinguish one image from another, that is, at 100 milliseconds or less. This requires a fast response time and an enormous amount of information. In the figure, color TFTs are divided into those suitable for display of motion, and information display systems that are intended for character, figure, and graphics display. Further, depending on the specific application for which a given product is used, the color TFT is divided into medium or high-definition display types.

Figure 1.3 shows the kinds of products developed so far. In video products, the color TFT is being used in viewfinders (VFs) and large-screen high-definition TVs, as well as car navigation systems. For information display, the color TFT is gaining ground in data processing and communication, ranging from portable computers and portable data communication devices to workstations (WS).

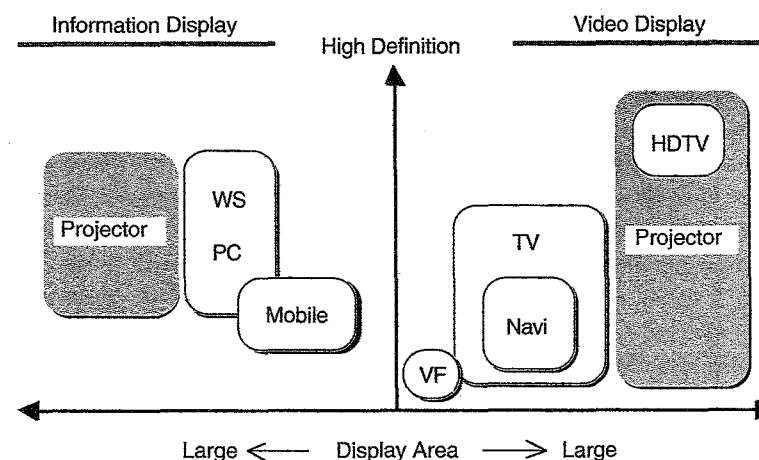


FIGURE 1.3 Display capabilities by application

In the above figure, the shaded sections indicate projection LC (liquid crystal) systems. A projection system works like a movie projector that forms an enlarged image on a screen. An overhead projector (OHP) is one example of a projection system. Front projection equipment works like a slide projector or OHP projector. On the other hand, in rear projection systems, the entire system is housed in a box, much like a TV set. A system that does not require projection, in which the LCD screen can be viewed directly, is referred to as a direct-view system.

Table 1.1 shows examples of display complexities for computers. A mobile computer is a specialized personal computer or word processor designed as a portable information tool. It can also be considered to be a multifunctional electronic notebook. A mobile computer often allows the user to enter data using a pen, exchange information

TABLE 1.1 Display resolution for computers

EXAMPLE	MOBILE	PC	WS	REMARKS
1	239x168			Zaurus: Sharp
2	240x336			Newton: Apple
3	320x256			Zoomer: Casio
4	480x320			General Magic
5	640x400			EGA: Enhanced Graphics Array
6	640x480			VGA: Video Graphics Array
7		800x600		SVGA1: super VGA1
8		870x640		SVGA2
9		1,024x768		XGA: eXtended Graphics Array
10		1,152x870		
11			1,152x900	
12		1,280x1,024		
13		1,600x1,200		

*: An entry occupying two columns is applicable to the genres represented by those columns.

by electronic communication, and perform intelligent information management functions. Personal computers and workstations have more complex information display requirements, as shown in the table.

There are de facto standards for personal computers. The EGA mode refers to the graphic system that was developed for the IBM PC/AT. The IBM PC/AT contained a feature that allowed an expansion in display functions by plugging a board and an adapter into an expansion slot. Recently, the more complex VGA has moved to center stage as the standard display. Further, because of the increasing popularity of software that permits multiple images on a single display, there has been an increase in the demand for super-VGA and XGA display units offering even greater display capabilities. Demand is especially high in countries whose languages are based on Chinese characters that require a two-byte-per-character display. In the XGA multiwindow environment, being advanced by IBM, displays are generated either by the operating system (OS) or by the application itself. As 32-bit architecture becomes widespread and as multi-task and multi-user computers become widely available, the boundary between personal computers and workstations will increasingly become blurred.

Color TFT displays are controlled by the bitmap method in which a one-to-one correspondence exists between a point on the screen and an address in the computer's internal memory. In the bitmap method, the entire screen is divided into a grid, and each grid point, called a pixel, contains information that regulates the color and brightness of the display generated at that point. The amount of information (the number of bits) stored at each

pixel determines the screen's display capability, including brightness. The display of 1,677,000 colors, equivalent to the information available in a color photograph, requires 24 bits of information (8 bits each for the RGB in 256 gray scales). The color TFT is capable of displaying this range of natural colors and can handle the analog grayscale corresponding to a continuous change in color.

The greater the number of pixels composing a screen, the greater is the display's ability to produce detailed images. Usually, this is accompanied by a corresponding increase in screen size. A high pixel density also requires high-speed drive circuit technology capable of addressing an image within a short frame time.

A home TV screen is composed of scanning lines, corresponding to the number of vertical pixels, and a horizontal resolution, corresponding to three-fourths the number of horizontal pixels in a color TFT. A typical TV set contains approximately 250,000 pixels ($525 \times 360 \times 4/3$). Some broadcasting stations beam approximately 350,000 pixels ($720 \times 360 \times 4/3$) and thus produce more detailed pictures.

Figure 1.4 shows the row and column pixel count for the displays indicated in Table 1.1. Table 1.2 shows the product of row and column pixels. A VGA monochrome display corresponds to about 310,000 pixels. As the examples in the table show, a wide range of display capabilities, from 40,000 pixels to 1,920,000 pixels, is being used in computing.

Table 1.3 shows examples of images used in data communication in which compressed images are transmitted by encoding. This type of encoding is used in VCR and CD-I (interactive compact disc) recording. The display resolutions indicated in this table are estimates drawn

TABLE 1.2

Example	Pixel Count
1	40,152
2	80,640
3	81,920
4	153,600
5	256,000
6	307,200
7	480,000
8	556,800
9	786,432
10	1,002,240
11	1,036,800
12	1,310,720
13	1,920,000

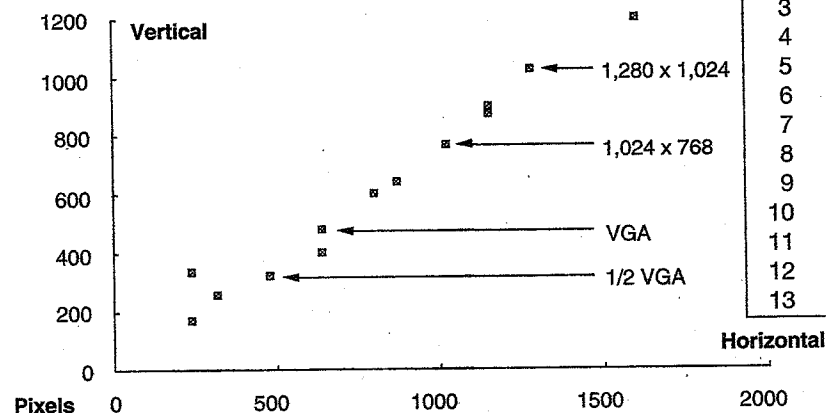


FIGURE 1.4 Distribution of the display resolutions of Table 1.1

from broadcast TV signals. The motion pictures that are suitable for data compression are intended for mobile information devices requiring low transmission rates and data is transmitted through relatively low bandwidth communication channels. In order to transmit information without degrading the image quality, temporal resolution must be reduced, by reducing the update rate. This, in turn, may produce a somewhat jerky image and may

TABLE 1.3 Display resolutions and the picture communication environment

EXAMPLE	PIXELS (HORIZ. X VERT.)*	APPLICATION
1	90 x 60	TV phone (mobile)
2	180 x 120	TV phone
3	360 x 240	Teleconferencing
4	720 x 480	Broadcast TV

* Image resolution with waveform encoding

require a reduction in the size of the display area to render it less objectionable. Encoding techniques for compressed images are needed in order to minimize the reduction in picture quality even when super-low transmission rates are used. As mobile computers incorporating portable phones and faxes gain wide acceptance and with the advent of an era of satellite-based data systems, a mobile communication environment will become practical in which high-quality motion pictures can be transmitted through wireless communication.

Among hardwired systems, the Internet, a network of computer networks, is a relatively new personal computer communication system using telephone lines. The Internet began as a network linking academic users. In Japan, it commenced with commercial services in 1993 through service companies. Worldwide, the Internet now links over 20 million users in 143 countries. Over 25,000 networks can be interconnected to the Internet. In addition to offering news and electronic mail services, the Internet offers vast amounts of information, including data, some of it free-of-charge, and a variety of video information. As the speed, cost, picture quality, and voice quality of communication improve, personal computer-based communication services will become powerful interactive media.

Cable TV is also moving toward visual databases and data communication services. The construction of information services integrating communication satellites, broadcasting satellites, and cable TV is being envisioned. A cable TV circuit can handle the transmission of 500,000,000 bits per second of information compared to the 28,800 bits maximum data transmission rate that can be supported using a modem attached to a PC. If a personal computer

TABLE 1.4 Data display capabilities of Photo CDs

EXAMPLE	PIXELS		IMAGE APPLICATION
	(VERT. X HORIZ.)*		
1	128 x 192		Video monitor BASE IMAGE * HDTV Hardcopy, printing
2	256 x 384		
3	512 x 768		
4	1,024 x 1,536		
5	2,048 x 1,536		
6	4,096 x 6,144		

*: Based on TV-like resolution

were connected to a cable TV line, it could easily handle motion picture reception.

Table 1.4 shows the amount of data stored in a typical photo CD. The photo CD, which allows you to view photographs on a TV set and which is used to produce multimedia titles, stores display data at several levels. Relative to the base image level (512 x 768), image data stored on a CD can be enlarged and reduced by a factor of 16 in each direction (from 2,048 x 1,536 to 128 x 192). The PRO Photo CD, which is an enhanced version designed to handle even larger data capacities, can record 16 to 64 times more data (4,096 x 6,144), except for TV playback. The PRO Photo CD is gaining popularity because of its ability to easily store high-quality images in a personal computer.

In 1993, the White Book joined two other CD media standards, the Red Book and the Yellow Book. The Video CD that records animated pictures compressed by the MPEG method is based on the White Book standard. These CDs can record up to 74 minutes of full-motion and full-screen animation pictures with digital sound. Currently, CD media manufacturers are developing proprietary standards, such as CD-I and 3DO, that are extensions of the basic Video CD standard.

When we watch a color TFT screen, we view the light values that are produced on the color filters elements. There are different kinds of color filter arrays, such as arrays in which the RGB pattern is arranged for ease of generating characters, graphics, and other linear displays; and patterns designed to produce continuous images of unpredictable forms, such as video pictures. Many elements, such as display backlight emission spectra and contrast, are adjusted to match the panel characters of the color screen. This adds another dimension of complexity to the design and fabrication of color TFT displays.

1.2 DEVELOPMENT OF TFT LCDS

The research and development of the LCD in Japan date back to the late 1960s and early 1970s. During this period, several companies battled for technological supremacy. Now, however, they are striving to reduce product costs while increasing LCD display performance. The advent of the color TFT in the LCD industry brought the wall-mounted TV set within the realm of practical use.

1.2.1 Actualizing Color TFT LCD Displays

Figure 1.5 shows the time frame in which major new LCD products were introduced into the marketplace. The TN (twisted nematic) display, which was commercialized during the first half of the 1970s in a succession of product releases, accounted for most of the LCD market until the next generation, STN mode display, made its appearance. Even now the TN mode is used in almost all home electrical appliances, audio visual equipment, game machines, and industrial machinery. STN displays use super-twisted nematic liquid crystal material, which permits

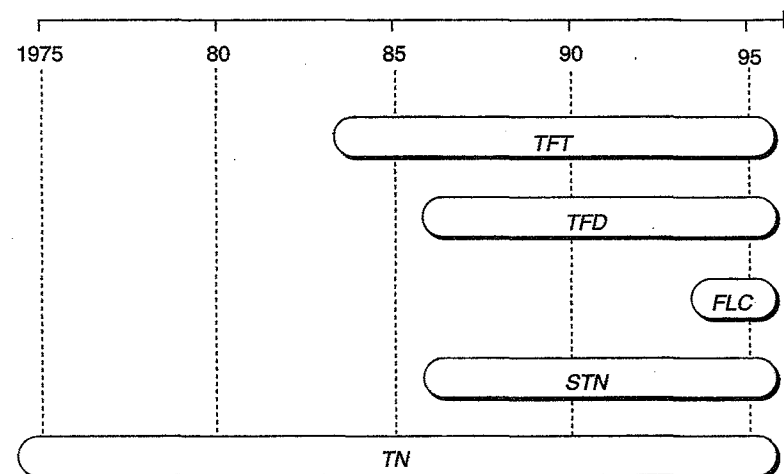


FIGURE 1.5 Timeline for the market expansion for major LCD types

multiplexing thousands of pixels. The increase in display performance made possible by the introduction of the STN mode prompted the spread of portable word processors and personal computers beginning in the second half of the 1980s. At the same time, the STN mode rapidly increased the market size for LCDs. The FLC (ferroelectric liquid crystal) display is a newcomer, and it is intended for large screens with a diagonal size of 50 cm or more. The thin film diode, TFD, of which the MIM (metal-insulator-metal) type is the main example, is mostly found in portable color video units. In the future, TFDs will find their way into mobile computers and word processors as well. This technology is likely, eventually, to produce large screens of 25 cm diagonal or greater.

Until the beginning of the 1980s, LCDs were principally used in wristwatches and calculators. Early entrants were clearly divided into two camps as far as R&D

strategy was concerned. The first group were companies that were eager to gain short-term market adaptation by producing new display products designed to replace the traditional hands on a watch's dial. The other group was composed of companies that were intent on conducting long-term R&D efforts in order to produce displays for new products. In the ensuing years, the growth of the calculator business leveraged the second group of companies into the driver's seat. The wristwatch LCD, which offered only a limited number of display elements, was improved on the drive circuit side, including the introduction of multiplex drive, and the voltage averaging method that uses alternating current. CMOS-LSI technology helped to reduce the amount of power consumed by drive circuits. The resulting performance improvements made it possible to incorporate LCDs in calculators. That occurred around 1975, the beginning of strong growth in the LCD industry in Japan, and the rapid increase in the output of LCDs made the business a profitable one. At the same time, mass production methods were devised that significantly increased the production rate of LCDs. The development of methods for the manufacture of a large number of LCDs from one piece of glass helped to reduce the unit production cost. These technological innovations were achieved by joint development efforts between display manufacturers and materials and equipment suppliers.

About 1980, LCDs offering higher performance than calculator displays appeared on the market. Each year saw the development of increasingly larger display products. Figure 1.6 shows how the amount of information that a display can reproduce has increased in the past two decades. Each performance increase created new end products.

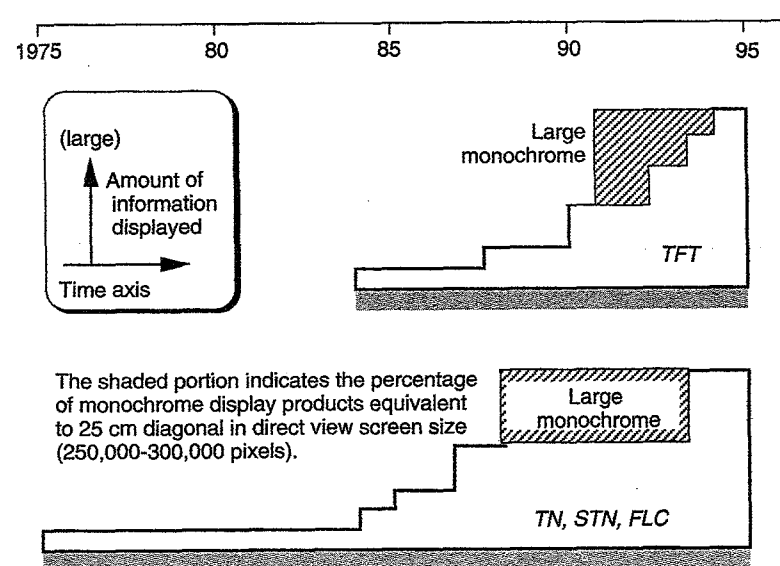


FIGURE 1.6 Change in the amount of information displayed: based on actual production volumes

During the second half of the 1980s, when the passive matrix TN mode device reached its performance limits, the STN display appeared. This development was timely indeed. The personal computer industry began to grow in tandem with STN technology. Few notable developments occurred after 1991-1992 until the fall of 1992, when STN technology introduced a color display function to the marketplace. Since the second half of 1994, the color STN has assumed a large presence on the market, complementing the color TFT. Qualitatively, the addition of RGB produced a threefold increase in display capability. However, the upper limit on display size for STN is 25 cm, with a maximum number of pixels of 900,000 (640 x RGB x 480). Aggressive research efforts are being undertaken to

improve the response speed and the viewing angle. Research and development of the ferroelectric liquid crystal mode or FLC mode, designed to achieve further increases in the display capacity with improved picture definition, are also under way.

The first color TFT product was announced in 1983. The following year, products with a 5-cm diagonal display size appeared. By 1990, the mass production had advanced to 100,000-200,000 pixel displays up to a 15-cm diagonal size. Today, direct view color TFTs can be produced in volume, with 300,000 to 900,000 pixels or more, up to 20 cm - 30 cm in diagonal size. Increases in the display size have led to continuing increases in the substrate size. This has resulted in additional improvements in the production efficiency. At present, substrates measuring 400 mm x 500 mm are used in mass production, and four to six displays can be made from one substrate. There will be another 150 mm increase in substrate size, to 550 mm x 650 mm, in just a few years. In addition, improvements to increase vertical viewing angle, reduce power consumption, and eliminate spurious reflections will be incorporated into the color TFT.

The capability of the color TFT display has already reached a critical level. Direct-view color TFTs are available for workstations and high-end personal computers that require high resolution and large screens. Displays for high-end HDTV, which require an even higher resolution, can be implemented in TFT liquid crystal projection devices containing up to 4 million pixels, projected onto a screen that measures up to 5 meters diagonally.

Figure 1.7 shows advances that have occurred to date and areas in which new products are being developed. The

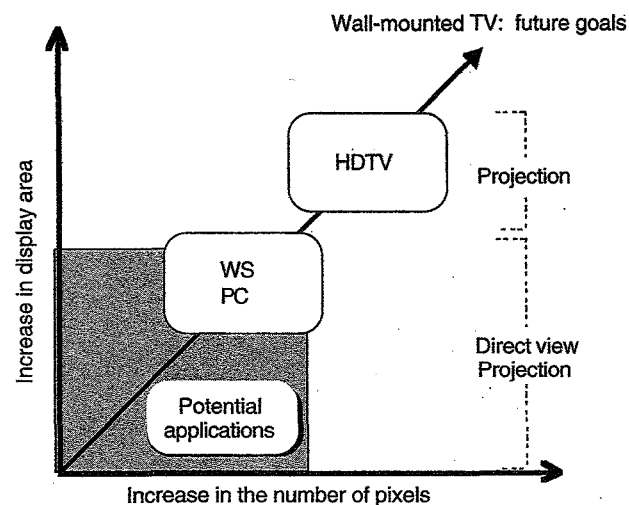


FIGURE 1.7 Development of new applications

shaded portion indicates an area for which new products are still being developed and new color TFT displays are being designed. Examples of notable new product concepts include Sharp's LCD ViewCam, Apple's Newton, and TFT advertisements displayed on some railway cars in Tokyo. IBM's new "green" PC desktop computers feature the color TFT display. Incorporating VGA technology with a 10.4-inch screen size, the desktop personal computer, which now takes up a large portion of your desk space, will shrink in size to that of a desktop clock, so that you can move it around with one hand.

1.2.2 Creating Applications

(1) Market Scope

There are a wide variety of products that incorporate the color TFT. Figure 1.8 shows application-by-application

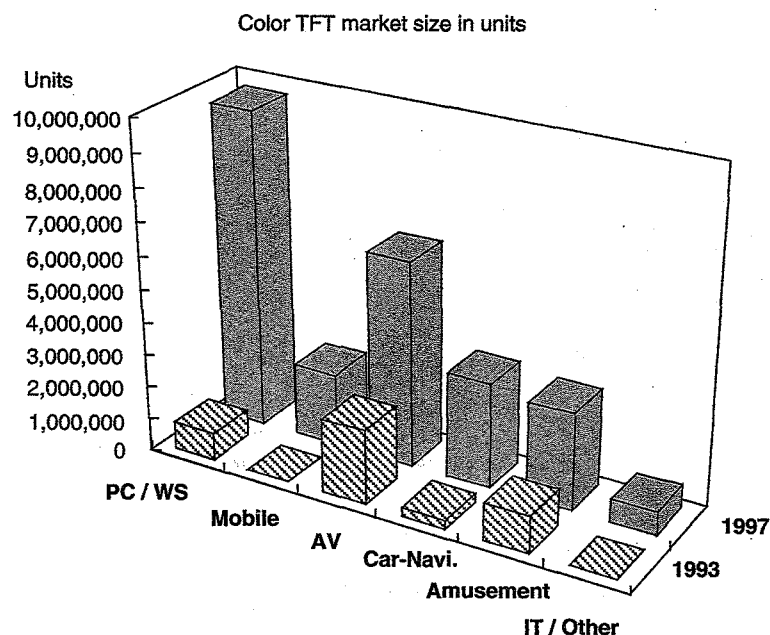


FIGURE 1.8 Color TFT market size in units

market sizes in terms of units, 1993 (actual) and 1997 (projected), for six product categories. The projected market sizes were estimated in terms of expected demand for existing products and in terms of plans for the construction of mass production facilities. Each segment of the market is summarized below.

Personal computers and workstations show the greatest gains. In the case of personal computers, the most popular screen size, in diagonal measure, is shifting from 21 cm (8.4 inches) to 24 cm (9.5 inches) to 26 cm (10.4 inches). These sizes correspond to the maximum screen sizes that can fit in an A4-size notebook PC. VGA is the display mode used on these screens. In the case of workstations, screens

measuring 28 to 36 cm (11-15 inches) are being supplied to the marketplace. However, when compared to personal computers, the volume of production is not significant.

Mobile computers are poised to take off. The principal requirements are low power consumption, on the order of 2-3 W for color TFT modules that include backlighting, and a module thickness of 7 millimeters. The screen size will be in the 12-20 cm range (5-8 inches). These devices include what used to be called "palmtop personal computer". Mobile computers and personal computers will overlap in functionality, and may ultimately be treated as a single category.

Audio visual equipment is the product area in which color TFTs first appeared. This is a field teeming with products. Direct-view audio visual equipment screens range in size from 2 to 43 cm (1 to 17 inches), and projection screens range up to 500 cm (200 inches). In this field the color TFT will become dominant in all sizes, from the smallest to the largest.

Automobile navigation systems based on the Global Positioning System (GPS), which provides position, speed, and time information at any location on the basis of information beamed from 24 satellites orbiting the earth, have become increasingly popular. The automobile navigation system also allows the motorist to enjoy games and music information using CD-ROM. As communication services become widespread, the latest traffic information as well as detour information can be obtained instantly. Eventually, users who are on the go will be able to enjoy the same availability of information as they do at home or in the office. For this application, screens ranging from 8 to 15 cm (3 to 6 inches) are employed. The dashboard,

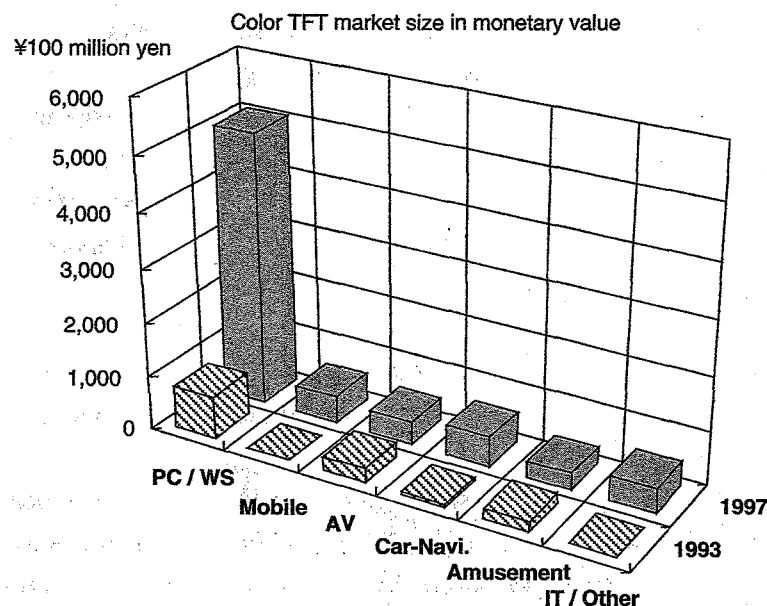


FIGURE 1.9 Color TFT market size in monetary value

crammed with a speedometer and other instrumentation, is a high-information-density area. The color TFT, offering a wide viewing angle and a broad operating temperature range, is well suited for such an inhospitable operating environment, with extremes of temperature and humidity.

The term "amusement equipment" refers to leisure-oriented devices such as portable game machines, pachinko equipment, and karaoke sets. The color TFT meets consumers' requirements in this large marketplace. Most amusement equipment will feature a 7-10 cm (3-4 inches) screen size.

Although modest in absolute volume, intelligent terminals (ITs) and monitors, which form part of the "other"

category in Figure 1.8, are high-profit-margin commodities. When it becomes possible to receive and transmit video information by means of mobile devices, intelligent terminals and monitors will receive wide acceptance for industrial use. The item "other" also includes airline cockpit displays and a variety of other special applications.

Figure 1.9 shows the market size for color TFT by market value, using the same basic data as in Figure 1.8. Figure 1.9 clearly indicates that the personal computers and workstations segment is head and shoulders above the rest. In terms of both number of displays and display market value, the PC is the largest application for the color TFT. Figure 1.10 shows the worldwide market size for personal

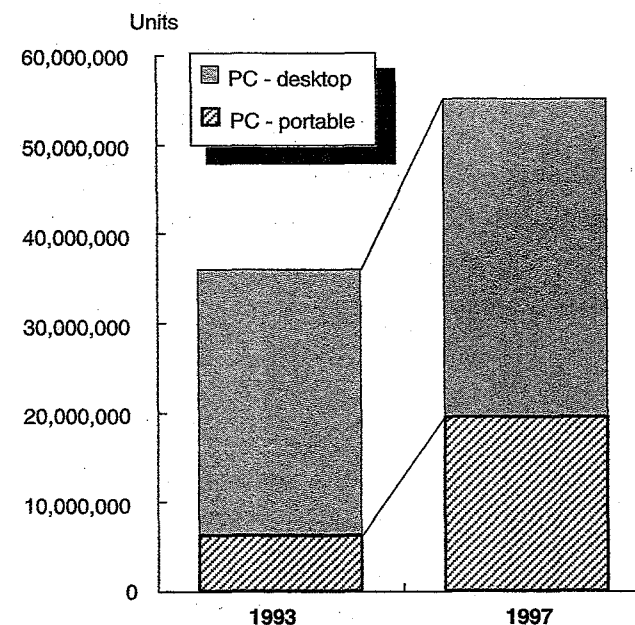


FIGURE 1.10 PC market size by unit

computers. The shaded portion of Figure 1.10 indicates the potential market for the color TFT.

The Japanese market for personal computers has experienced a rapid price decline. Undercut initially by IBM PC clone makers, prices have dropped substantially since 1992. In terms of shipment volume, PCs have been posting double-digit growth thanks to the migration of Japanese PCs toward a multiwindow environment based on DOS/V platforms.

In the future, personal computers will increasingly become simply components. Faster and smaller personal computers will be incorporated into a wide variety of products. Thus, the PC is moving towards becoming an invisible device. The key to accomplishing this is a superior user interface. The ideal situation would be an operating environment in which the personal computer, as a piece of hardware, is completely transparent to the user. Increasingly, personal computers will become tools not only for data capture and manipulation, but also for fun and communication. As long as the color TFT continues to offer both the technology and values that contribute to the growth of the computer industry, a bright future will await the color TFT.

(2) Towards the Information Age

Our communication environment, supported by the spread of data communications, is becoming an enormous information network. When connected by faxes, you feel closer to someone living in San Francisco than to your next-door-neighbor living in Tokyo if that neighbor does not have a fax. Thus, in terms of information transmission, the conventional map that merely indicates how physically

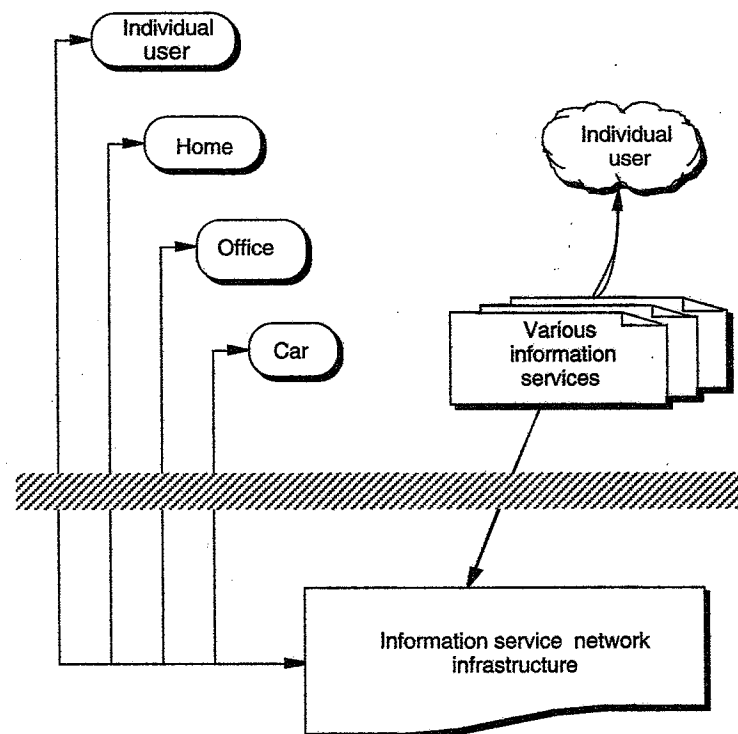


FIGURE 1.11 Image of future data communication services

close you are to a certain location or how far away from it is no longer very meaningful. We need maps that indicate proximity or remoteness in terms of information access. Advancement in data communication technology is steadily expanding our perception of the world.

Figure 1.11 shows an image of the flow of information services in a future communication network. It will not be long before individuals will be able to communicate with many persons under a variety of circumstances by using both hard wired and wireless forms of communication.

Networks designed to provide services that handle diverse information requests from individuals must incorporate a mechanism that stores, converts, and transfers information. Future homes may have mobile communication device outlets, similar to the electrical outlets now found in most homes. Information devices that control virtually everything from air conditioning to the physical security of the home may become as commonplace as TV sets. In offices, the telephones, faxes, and personal computers that comprise separate networks may become integrated into a larger network so that different machines can exchange information freely. A new genre of software called "groupware," which allows a group of people to work together through the use of information technology, is gaining acceptance. With groupware, individuals can send and receive information and instructions freely on their own terminals, across time, geographic, and organizational barriers. People will be able to share information even when in an automobile or some other form of transport. Various technologies will become dependent on data communication technology in one way or another.

Figure 1.12 shows the functional components of personal, portable data communication devices that are expected to be in common use in the near future. Although important functions are communication and information management, users may demand products that incorporate virtually all functions, including those of the pager, the portable phone, the electronic notebook, and the electronic book. Voice input and response technologies are being developed. We have pursued accuracy and speed in personal computers. We have commanded the PC to follow us everywhere, and required it to handle

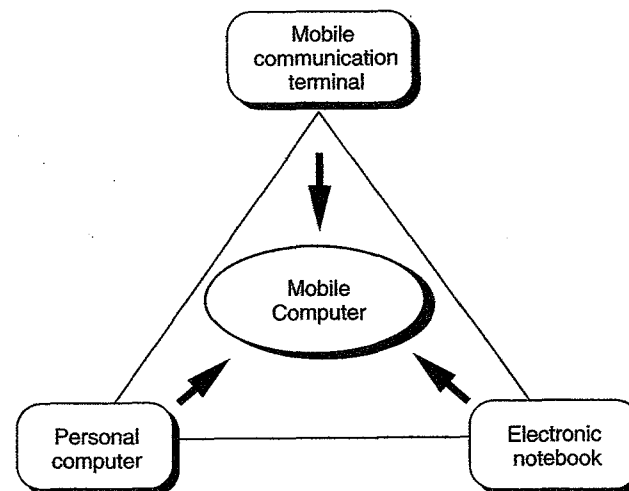


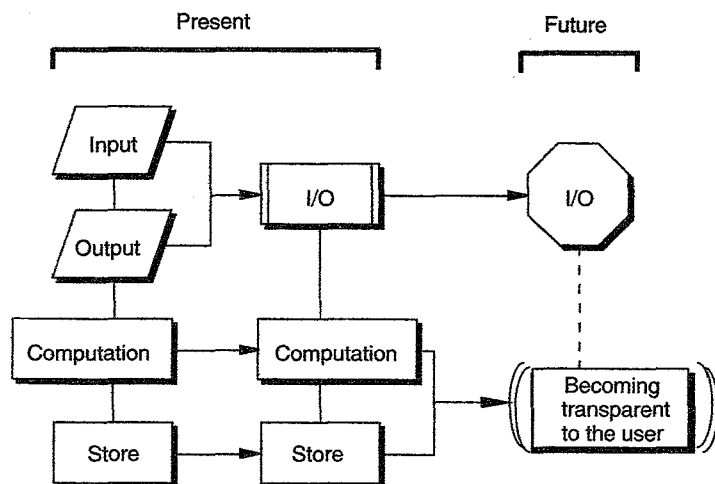
FIGURE 1.12 Mobile computer components

communications with the entire world. The PC, barely age 12, is undergoing a tremendous evolution while coming into contact with a variety of new environments. The mobile computer is a new species that has been spawned as a result of this evolution. It will grow as a personal tool practically tailor-made for sophisticated data communication infrastructures. Wherever you go, the place at which you work or play will become your information base.

1.3 THE WORLD OF TOMORROW

1.3.1 Role of Computers and Displays

Conceptually, the functions of a computer can be classified into input, computation, storage, and output. In a main-frame computer, the functions of input, computation, and storage represent the bulk of the work performed by a

**FIGURE 1.13** PC functions and forms

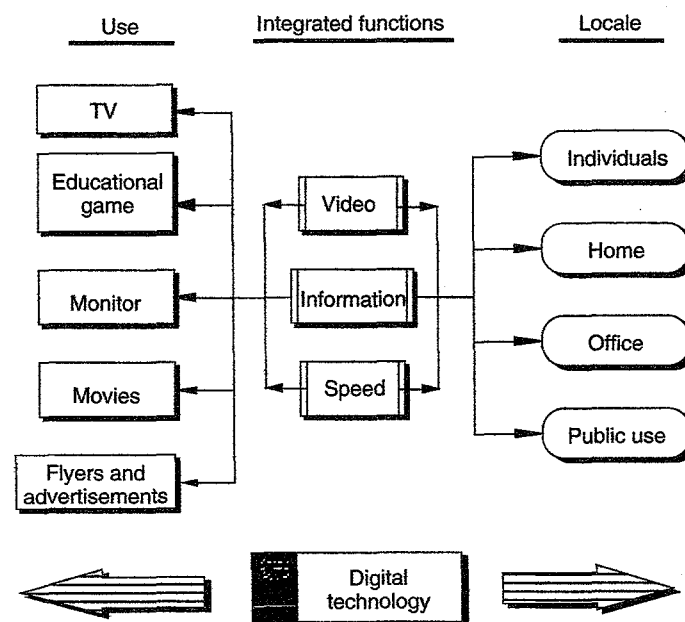
computer. By comparison, output plays only a limited role. At large computer installations, the information on how the facility is operating is only output on a monitor for verification purposes. In a personal computer, however, controlling output and modifying and displaying input data are the key elements in its use. Therefore, the display is a more important component than for mainframes.

Figure 1.13 shows how the form of personal computers is undergoing a change as their functions become more integrated. Portability is enhanced with pen-input models, in which input and output are integrated. An input pen can both serve as a pointing device, similar to a mouse, and eliminate the need for a keyboard. Computers that allow voice-based input, output, and response, would be even easier to use. Further possibilities include input sections with sensors for image identification and motion detection. The color TFT is likely to play an important role

as a device that simultaneously supports both input and output functions.

Figure 1.14 shows the principal uses of displays and centers on three points at which the functions are integrated. A display must show motion, as well as pictures and information.

Paper was the first computer-user interface. The programmer would feed signals, punched on a piece of paper, into the computer and would receive processing results in the form of punched paper. Subsequently, improvements in the computer's processing speed made paper-based I/O

**FIGURE 1.14** Display functions, application, and locale

obsolete. Personal computers, are moving toward the time when they will be just like a piece of paper. In such a computer, the other functions of a personal computer are all incorporated into the I/O section, so that, in external appearance, the computer will be a transparent piece of equipment.

It is often said that, if we are to measure the advances made by the computer over the past 40 years in terms of five indexes, storage capacity, reliability, cost, and processing speed, the overall progress that has occurred is a number expressible in 30 digits, which is equivalent to enlarging the diameter of an atom to the diameter of the Milky Way. Now comes the display. Displays were created to allow output to keep pace with the internal processing speed of the computer. As the computer's processing speed continues to improve, the accuracy of the monitoring activity also improves, and the monitor acquires an increased ability to express information. Our perception of the computer's speed is directly influenced by the way the user interface is designed. The processing speed of a computer is now so fast that it cannot be expressed adequately by means of ordinary instruments. The results of processing, produced at unimaginable speeds, can be rendered meaningful to us only if they are generated as video images. Thus, the computer as a communication medium has acquired the power of expression.

The types of services that can be offered in various applications will change significantly because of digital technology. For each application, the importance of the display will increase. The next section provides an overview of this development.

1.3.2 Multimedia

There is no clear definition of what "multimedia" is. Therefore, there are many different interpretations of the word multimedia. In the literal sense, "multimedia" means the integration of multiple media. The goal is a world in which computers, communication, and TV are fully integrated, and information is used in a dynamic state. Multimedia may be thought of as an attempt to standardize all forms of information expression, such as characters, sound, still pictures, motion pictures, photographs and other images. In communication and broadcasting, attempts are being made to expand networks, and to digitize sound, still pictures, and motion pictures. In information processing, the multimedia function is a means of simplifying operation and control through visualization. In movies, games, broadcasting programs, music, and publishing software, work is continuing to digitize already existing resources and to develop interactive software with mass appeal.

The following discusses multimedia both as a function and multimedia as an industry.

(1) *The Role of Multimedia*

The current function of digitized media is similar to that of a book. With a book you can view any part of it at any time, and you can read it in any way you wish. You can either peruse it or skim it. There is nothing to prevent your referencing a second book while reading the first, or pausing for a moment to reflect upon what you have just read, and then returning to the book as your whim dictates. Indexes and lists of references support these activities. In

multimedia, these uses for books can be enlarged. For example, a structure called "hypertext" can instantly take all the pages of a book apart and sort them in a different order. It can also very quickly determine how many times a given word occurs in the book or in a given section of the book. With the addition of communication facilities, hypertext also allows you to reference information that is stored in a remotely located database. Ultimately, multimedia will allow you to modify and edit information any way you wish. Thus, multimedia will provide the opportunity to exercise your creativity.

The appeal of the personal computer to most users lies in the fact that it allows the user to perform all necessary tasks independently. The people who designed and developed the first personal computers created the machines that they themselves wanted to use. Those computers found their way to the marketplace, leading to the birth of the PC industry as we know it today. The creators of the PC found market needs within themselves, and satisfied those needs. In the multimedia movement, which is beginning now, new ideas may emerge and a new culture may arise from the ideas of people who are gaining satisfaction from the use of game machines and personal computers.

Figure 1.15 is a diagram depicting the functions of multimedia and multimedia elements. Multimedia combines the advantages of a book and TV, with interaction in realtime.

(2) Multimedia Industry

New media are being created as a result of the electronics revolution. A decade ago fiber optics created a "new media" boom. At that time interest was centered on the

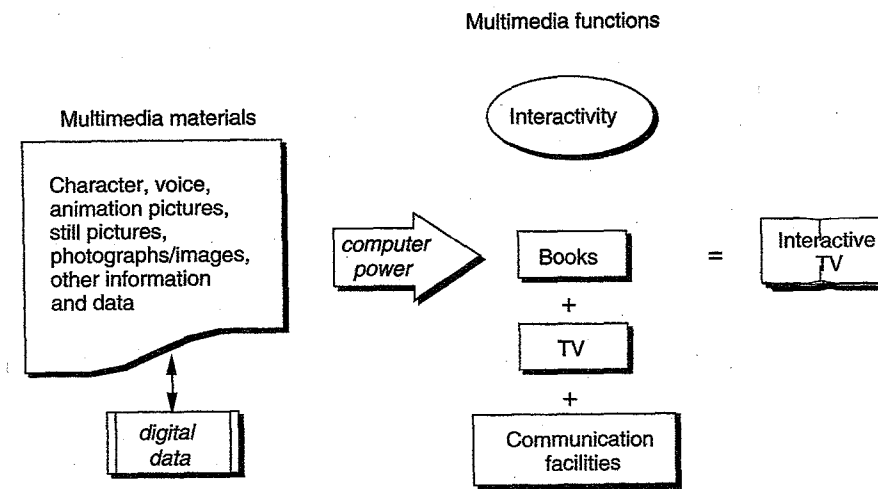
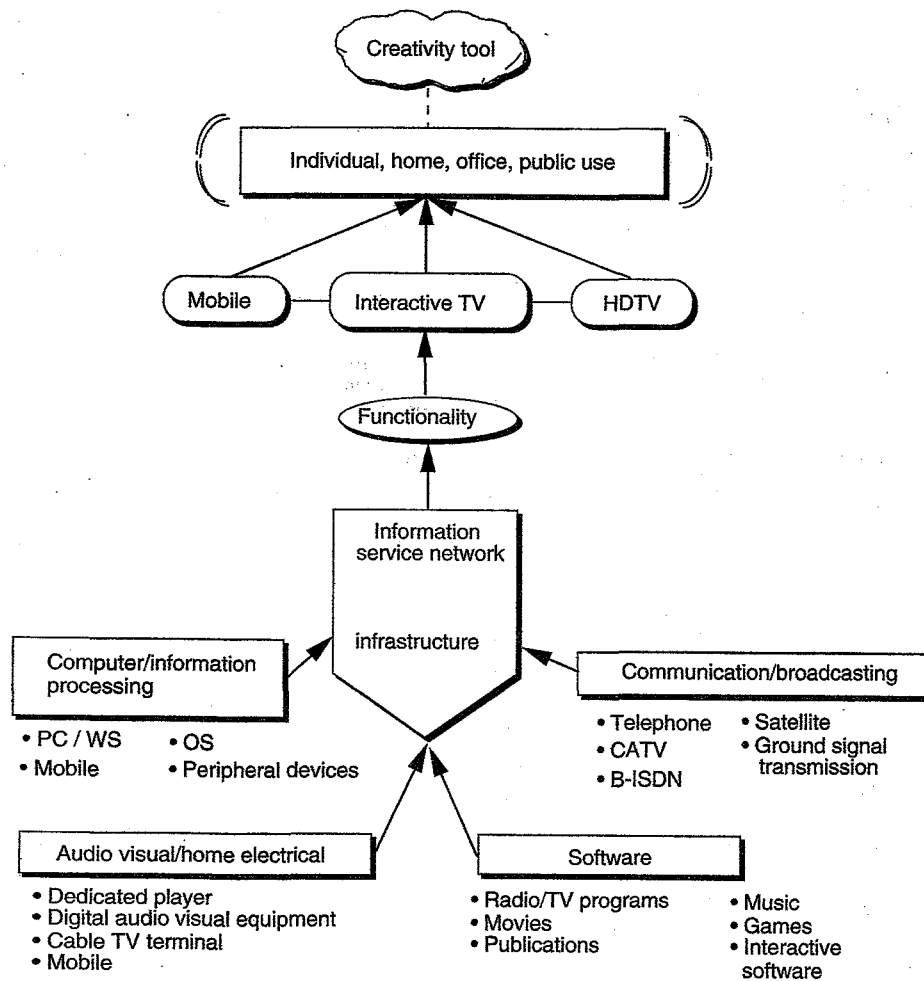


FIGURE 1.15 Multimedia materials and functions

construction and renovation of data communication infrastructures, with little attention given to improvements in software or peripheral devices. Multimedia in 1994, by contrast, is characterized by the amount of attention given to these other components.

Figure 1.16 shows an overall picture of multimedia as an industry. The multimedia industry, which is divided into four categories, is the foundation of an extensive information service network society. Centered on interactive TV capable of utilizing digital information, both portable data communication devices and HDTV will be, in effect, computer terminals. In a variety of situations, people will begin to enjoy the process of computer interaction.

The TV set, as currently known, lacks much in terms of picture quality. It is difficult to display characters and graphics in a quality comparable to that available on film and in print. When we watch TV, most of the time we watch the entire screen. On the other hand, when we use a

**FIGURE 1.16** Multimedia industry overview

PC monitor, we perform most work and operations by focusing attention on a specific portion of the screen. In order for interactive TV to become a means of information delivery, the quality of the picture must be improved. The standard likely to be adopted is the VGA mode (640-720 x 480 dots) or something similar. In the multimedia environment, an important requirement is that the individual pieces of information be independent elements. The reason is that the video image is not necessarily the most important part of the multimedia display. There are likely to be text and graphics displayed on the screen at the same time. Images must be displayed in full color that approximates the original color, as well as in monochrome. Video and sound must be synchronized as well. The coding method will be based on non-interlaced display scanning. A flexible design that allows the user to select the picture quality according to the source of the information to be displayed is also an important requirement.

The wider the range of services that can be offered, the better. More and more CD-ROM titles featuring works of art, library materials, and educational information are appearing on the market. Work is underway to digitize the vast stores of information available in other forms. There will be electronic art museums, libraries, and educational facilities offering database services. As communication costs decline, newspapers, news services, video software, and game software will be offered over the wire. This information will then be available to everyone, no matter where they are located. This might be especially useful for providing services such as medical diagnostics in remote locations.

Thus far, we have discussed multimedia as a new form of communication. We shall now consider business opportunities in the information infrastructure. On January 6, 1994, the Ministry of Posts and Telecommunications announced a long-term vision for the data communication industry in the 21st century. According to their plan, the installation of fiber optics throughout Japan will create a new market amounting to ¥56 trillion (\$560 billion). Besides this, the multimedia market is projected to reach a ¥123 trillion (\$1.23 trillion) in size. Data communication will become one of the basic industries in Japan, employing 2.4 million people.

Table 1.5 shows examples of large markets that could be created by multimedia. In many locations, huge software libraries will be on line 24 hours a day. This will substantially change the way we live and work. Governmental policies can encourage cooperation between companies and spur large investment. The fields of communication and software are emerging as important areas for both. The collaboration of companies to create the next generation of industry standards will be crucial.

TABLE 1.5 Market projection for communication technology-related products (in billions of dollars)

EXAMPLE	PRODUCT OR SERVICE	MARKET SIZE \$B
1	HDTV	30
2	Optical fiber subscription systems	5
3	Personal information communication terminals	5
4	Wide-area ISDN switches	2
5	Satellite data networks	2
6	CS-CATV/BS-CATV	1.4
7	Teleconferencing systems	1
8	TV phones	0.3

1.3.3 Information and Interface

The development of the flat panel display is accelerating along with these other developments in multimedia. Interactive communications through displays is almost here. The display is moving toward increasingly larger screen sizes and even toward 3D video systems. Visual information is growing more detailed and, voice is becoming closer to natural voice. Further, even taste, scent, and touch are being looked at as means of interface. The research on human sensory functions is expected to produce electronic interfaces superior to those we have today..

On the other hand, media will change the way we interact with the world. The accuracy and the speed with which information is obtained through media determine the way we make decisions. Thus, information has become a critically important resource, which can be used and manipulated by a large number of users. However, it will be quite some time before we become comfortable with the new media.

1.4 THE FUTURE OF COLOR TFT LIQUID CRYSTAL DISPLAYS

The demands of multimedia are creating better and better computing components, especially the display. If the core of a PC is the CPU, the display, which is the principal interface, must keep pace with improvements in the CPU and in multimedia. From this point of view, the future for LCD displays can be projected. In terms of functionality, the LCD can be divided into TN, STN, TFT, and others. These are selected according to their roles and applications. The TN display is used in calculators, remote controls, automobiles, and pagers, where the amount of information

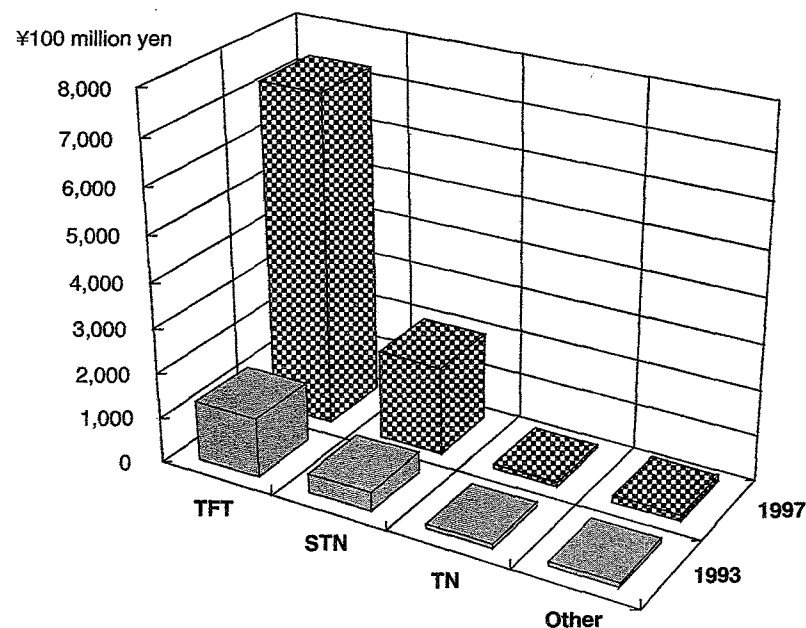


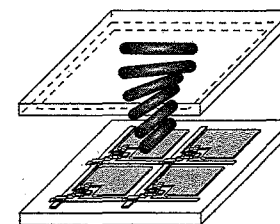
FIGURE 1.17 Color LCD market projection by type

displayed is relatively small. A color STN market is emerging in notebook personal computers and some amusement machines. The color TFT is capable of displaying a full range of colors for multimedia applications. High-speed driver LSIs for TFTs, capable of working in concert with a 100-MHz CPU, are yet to be developed. However, since driver LSIs are semiconductors, they will be able to achieve this high speed just as the CPU has been able to do. When this goal is attained, the market for color TFT in multimedia applications will expand, as shown in Figure 1.17. The display capabilities of a color TFT display will exceed those of the CRT. In terms of market needs driven by multimedia, the centerpiece for the future personal

computer market, the color TFT will evolve towards an ideal display, offering superior performance, functionality, and market appeal. Just as the LCD has grown in concert with semiconductor technology, the color TFT will grow hand in hand with the growth of multimedia. The future for the color TFT seems bright indeed.

CHAPTER 2

LOOKING INTO COLOR TFT DISPLAYS



2.1 THE LIQUID CRYSTAL STATE

As the name implies, a liquid crystal is a liquid substance that has crystal-like properties. Many types of liquid crystals with a wide variety of properties are known. They all share the common characteristic, however, that they exist as solid crystals at low temperatures, and when the temperature rises, they become liquid while retaining some of their crystalline properties. At higher temperatures, they become completely liquid.

As shown in Figure 2.1, a typical liquid crystal is a solid — a white, plastic-like substance, at a low temperature of -50°C . When the temperature is increased, the substance gradually becomes soft, ultimately becoming a clear, grease-like viscous liquid. Near room temperature, it loses much of its viscosity and turns into a syrup (Figure 2.2). It is in this state that the substance is called a liquid crystal, i.e., it exists in the liquid state but, optically, it exhibits

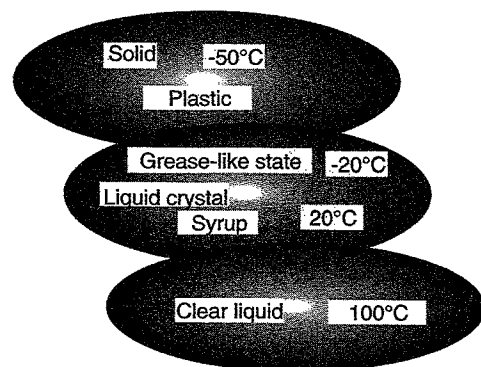


Figure 2.1 Example of a liquid crystal phase diagram

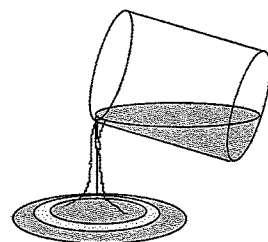


Figure 2.2 Physical appearance of a liquid crystal

crystal-like properties. A further increase in temperature, say, to 100°C, renders the substance completely into a clear liquid. This type of substance, which exhibits liquid crystal properties within a certain temperature range, is referred to as a liquid crystal substance, or a liquid crystal for short.

2.2 THE STRUCTURE OF LIQUID CRYSTAL MOLECULES

As shown in Figure 2.3, a liquid crystal molecule consists of two major components: a rigid, skeleton component and a component which is extremely supple, like a string. These components, having contrasting properties, give the liquid crystal molecule unique properties. As illustrated in Figure 2.3, the rigid components of a liquid crystal molecule are arrayed in regular patterns, much as crystals line up in a regular pattern. In the flexible component, on the other hand, the molecule moves freely. These opposite properties, endow the molecule with the free-flowing property of a liquid and the spatial regularity of a solid.

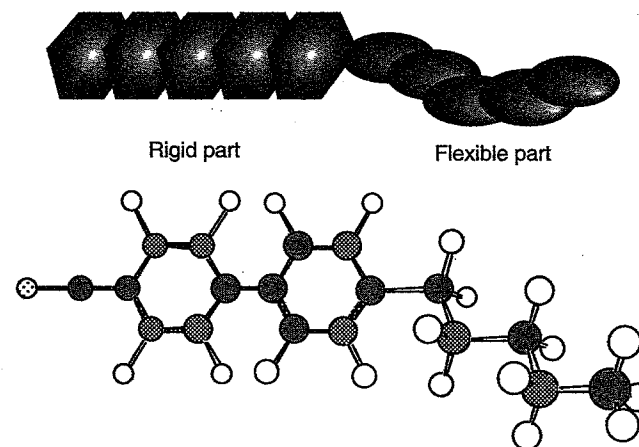
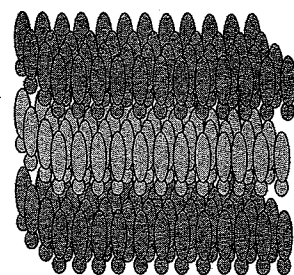


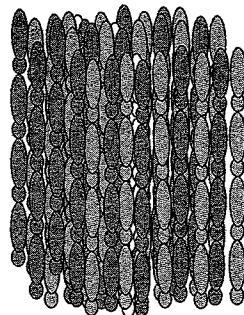
Figure 2.3 Molecular structure of a liquid crystal

2.3 TYPES OF LIQUID CRYSTALS

There are smectic (meaning "grease" in Greek) liquid crystals and nematic (meaning "string" in Greek) liquid crystals. Figure 2.4 shows an aggregate of these liquid crystal molecules. The particular state that liquid crystal molecules assume is determined by the mutual attraction between molecules. The specific structure of the molecules involved determines the relative strength of the intermolecular attraction acting along the long and short axes of the molecules. The balance between these forces determines whether a given aggregate of liquid crystal molecules is smectic or nematic. When the attraction acting along the short axis of liquid crystal molecules prevails, the smectic LC phase appears. This phase forms a layer structure in which layers can move freely. When the attraction acting along the long axis is strong, the molecules, instead of forming layers, become linked together like a string of beads. This is the nematic liquid crystal phase, in which the molecules can move freely in the direction of the long



Smectic liquid crystal



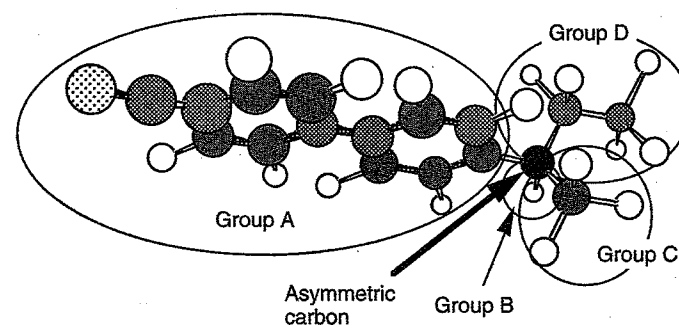
Nematic liquid crystal

Figure 2.4 Basic aggregation states of liquid crystal molecules

axis, but not in the direction of the short axis. A phase in which the molecules in a layer are aligned perpendicular to the layer in an array of smectic liquid crystals is called the smectic A (Sm A) phase. Similarly, a phase in which the molecules in a layer are inclined with respect to the direction perpendicular to the layer is called the smectic C (Sm C) phase. Altogether there are eight smectic phases, designated by the letters A through H.

Smectic liquid crystals change into nematic liquid crystals as a function of a rise in temperature. These changes are referred to as phase changes. Some liquid crystal substances exhibit only one liquid crystal phase, whereas others may exhibit different phases at different temperatures. All liquid crystals can operate only within a limited temperature range. Extensive research has been undertaken to increase the operating temperature range. As a result, by blending a wide variety of liquid crystals, it has been possible to develop liquid crystal compositions that have a useful temperature range from below the freezing point to the temperatures that prevail inside a car on a hot summer day.

In nature, optical isomers abound. Proteins are typical examples. There are also liquid crystals that exhibit optical activity. An optically active molecule contains a specific atom that is bound to atoms or groups of atoms that are all different. In the case of a liquid crystal, the specific atom is a carbon atom. As shown in Figure 2.5, the specific atom is bound to four groups of atoms, no two of which are alike. Such a specific carbon atom is called an asymmetric carbon atom. Two molecules containing asymmetric carbons can form non-superimposable mirror images of each other, similar to the right and left hands. Substances that contain these mirror images are said to have optical activity. The central atom in an optically active substance is called the chiral center atom. To differentiate one mirror image from the opposite member of the pair of mirror images, the symbols "l" and "d" are used. These non-superimposable mirror image molecules are called optical isomers. If an optical isomer exhibits optical activity, this fact is denoted by placing an "*" on the chiral center, on the molecular formula for the substance, or on the name of the substance.

**Figure 2.5** Molecule containing an asymmetric carbon (optical isomer)

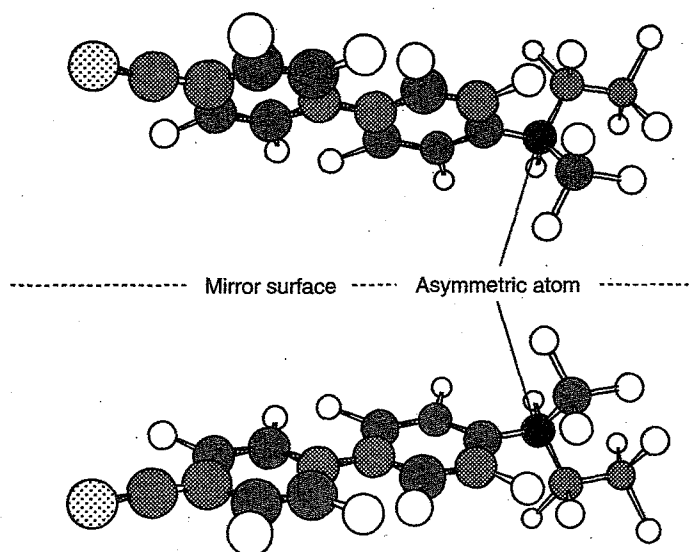


Figure 2.6 Mirror-image symmetry of optical isomers

Generally, in optically active molecules such as proteins, molecules are aligned in a helically rotating pattern. This pattern is also applicable to optically active liquid crystal molecules. Both optically active nematic liquid crystals and smectic liquid crystals form a helical structure, as illustrated in Figure 2.7. The period of a helical structure is referred to as the helical pitch. Likewise, the axis of a helix is called the helical axis. Molecules in which the helical pitch is equal to the wavelength of light have the property of selectively reflecting or passing the light of a

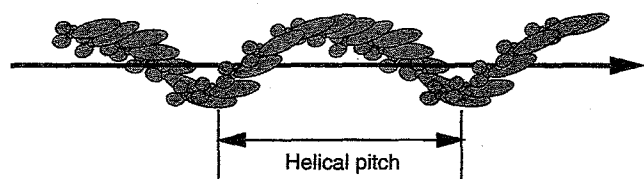


Figure 2.7 Helical structure of a chiral liquid crystal

specific wavelength. This property gives the molecules the ability to control light in a specific way.

Optically active nematic liquid crystals (n_e) are called chiral nematic liquid crystals. Historically, chiral nematic liquid crystals were discovered before (ordinary) nematic liquid crystals. Because some of the chiral liquid crystal molecules had a molecular structure similar to that of cholesterol, they are also called cholesteric liquid crystals. Similarly, some of the smectic liquid crystals, too, are optically active. They have intrinsic poles, and for this reason they are called either ferroelectric liquid crystals or chiral smectic (Sm^*) liquid crystals. The term "intrinsic polarization" refers to the fact that a molecule has a molecular bias in it, so that, when subjected to an external electric field, the molecules respond to the direction as well as the magnitude of the field.

Other types of optically active liquid crystals include those in which the ends of liquid crystals are linked beads-like with polymers, to improve their fluidity. These liquid crystals are called polymer liquid crystals. In the class of ferroelectric liquid crystals, there are anti-ferroelectric liquid crystals that have three levels of stable states and that exist in stable and quasi-stable states. There are also discotic liquid crystals, in which disc-like ester molecules containing benzene rings in their nuclei are stacked together. These liquid crystals exhibit unique properties. Also, there are re-entrant liquid crystals, which are smectic liquid crystals that revert to nematic liquid crystals at low temperatures.

All these liquid crystals, which share the common property that their liquid crystal state changes as a function of temperature, are called thermotropic liquid crystals.

By contrast, some of the amphiphilic substances that occur abundantly in nature and in organisms (substances, like soap, which are composed of hydrophobic groups, consisting of long carbon chains, and hydrophilic groups consisting of ions and hydroxy groups) can form liquid crystals in water. These liquid crystals are referred to as lyotropic liquid crystals.

The relationship among these liquid crystals is summarized in Figure 2.8. It should be noted that these names refer to either the material that composes a liquid crystal or the phase in which a liquid crystal exists.

2.4 LIGHT PASSAGE THROUGH MOLECULES

As shown in Figure 2.3, liquid crystals have a slender, elongated, rod-like molecular structure. Therefore, the way light propagates through liquid crystals depends on the

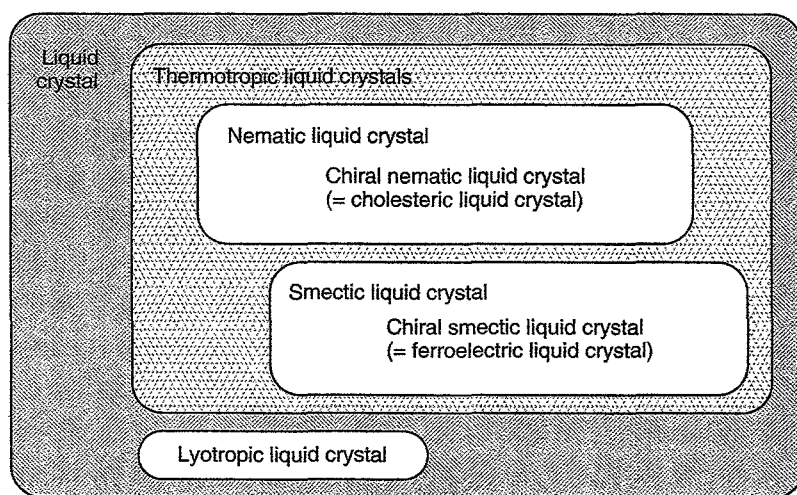


Figure 2.8 Types of liquid crystals

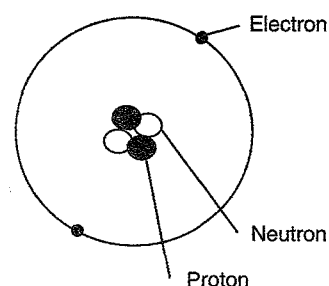
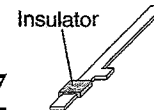


Figure 2.9 Bohr's atomic model

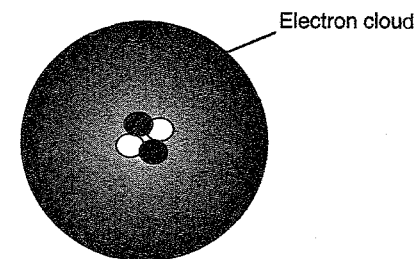


Figure 2.10 Electron cloud model

angle between the direction of the light ray and the direction of the molecules. To understand this phenomenon, we must first review the structures of atoms and molecules.

Normally, an atom is composed of an atomic nucleus (a set of protons and neutrons), around which electrons move at high speeds, as illustrated in Figure 2.9. In actuality, however, because electrons fly at high speeds, their positions cannot be determined, just as when the vanes of a fan are spinning at high speeds, you cannot see the vanes. As a result, the electrons appear as if they were a cloud covering the atomic nucleus. This is called an electron cloud. In a symmetric atom, such as helium, the electron cloud is spherical, as depicted in Figure 2.10. In the case of a spherical electron cloud, light encounters the same electron density, regardless of whether the light enters the electron cloud from the right or from the left.

Now, what would happen in the case of a substance, such as an oxygen molecule, that does not have a spherical electron cloud? In this case, if we can assume that the oxygen molecules do not move, the electron cloud assumes a pillow shape. In this case, the light entering the electron cloud from the left and that entering the electron cloud

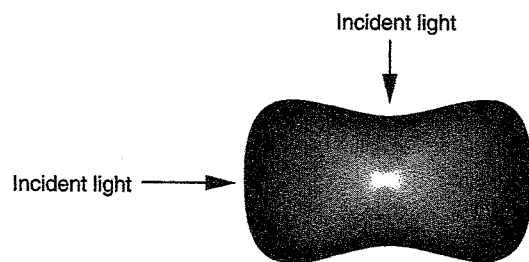


Figure 2.11 Electron cloud for an oxygen molecule

from above encounter spaces of different electron densities, as shown in Figure 2.11. In actuality, however, the law of average applies, because the oxygen molecule rotates at an extremely high speed and oxygen as a substance is an aggregate of a large number of molecules. Therefore, as in the case of the helium atom mentioned above, the light experiences a uniform electron density.

As a general rule, organic substances such as liquid crystal molecules are composed of atoms such as carbon, hydrogen, and oxygen. In this case, the electron clouds associated with adjacent atoms become mixed, forming a complex electron cloud as shown in Figure 2.12. When light enters the electron cloud of such a molecule under

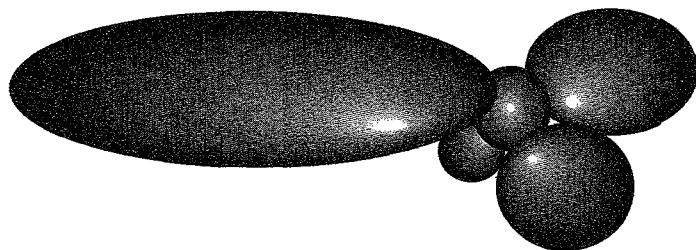
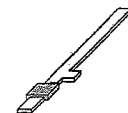


Figure 2.12 Electron cloud for a liquid crystal



certain conditions, the asymmetry of the electron cloud causes the light to bend or rotate, and allows the light ray oscillating only in a particular direction to pass.

To cause an optical rotation, or polarization, which admits the passage of light components that oscillate only in a specific direction, three factors are required:

- (1) Choosing molecules that have electron densities that are significantly higher along the vertical axis than along the horizontal axis, or vice versa. This type of uneven distribution of electron density creates a dipole moment.
- (2) Causing the molecules in a substance to align themselves.
- (3) Confining the molecules in a substance so that they do not move.

Polarization occurs when these conditions are met. Materials that satisfy these conditions include uniaxial crystals and uniaxial-oriented polymer films. A typical uniaxial crystal is calcite, and a typical uniaxial-oriented film is the polarizer film.

Let us now turn to the question of how a polarizer film produces polarization. A polarizer film is made by doping a polymer film, to which polyvinyl alcohol (PVA) is applied, with iodine. The iodine molecules in the film are aligned by uniaxially orienting the film. When given this treatment, the iodine molecules orient themselves together with the polymer in the film, thus turning to the same direction. Because iodine molecules contain unevenly distributed electron densities, they orient themselves when the film is drawn, and are immobilized in the film matrix. Thus, they satisfy the three necessary conditions for the production of polarization.

Let us now shine light onto a polarizer film from the left, as illustrated in Figure 2.13. Ordinary light always oscillates perpendicular to the direction of its propagation. Thus, ordinary light contains components that vibrate parallel (vertical) to the long axis of the iodine molecules in the polarizer film, and components that vibrate perpendicularly (lateral) with respect to the iodine molecule's long axis. Although there are light components that vibrate at angles that fall between these extremes, for the sake of simplicity we focus solely on the light components that vibrate parallel to the long axis and components that vibrate perpendicular to the long axis. In the case of iodine, the differences in electron density manifest themselves most significantly in different molecular optical absorption coefficients: whereas the light component that vibrates

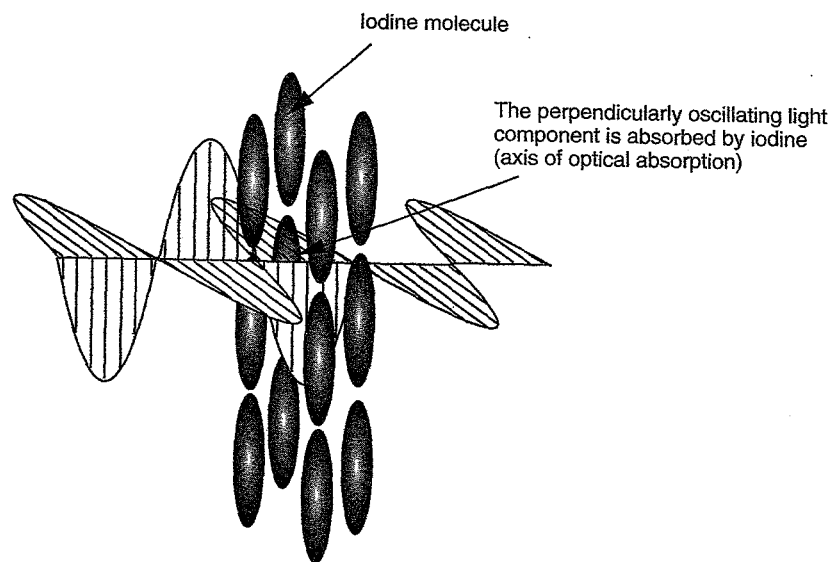
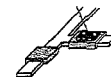


Figure 2.13 Light passing through oriented iodine molecules (polarizer film)



perpendicularly to the long axis of the molecules is transmitted virtually 100%, the light component that vibrates in parallel to the long axis of the molecule is hardly transmitted. Therefore, only the light component that vibrates perpendicularly relative to the long axis of iodine molecules can pass through the polarizer film; all other light components are absorbed by the iodine. It is in this manner that a linearly polarized light that vibrates only in one direction can be obtained from ordinary light.

Other methods for producing polarization exist, such as using a double-refraction prism. However, since these methods are seldom used in LC displays, they are not discussed in this book. At any rate, although different underlying principles come into play, the result of using a polarizer film is the passage of polarized light that vibrates only in a specific direction, as illustrated in Figure 2.14.

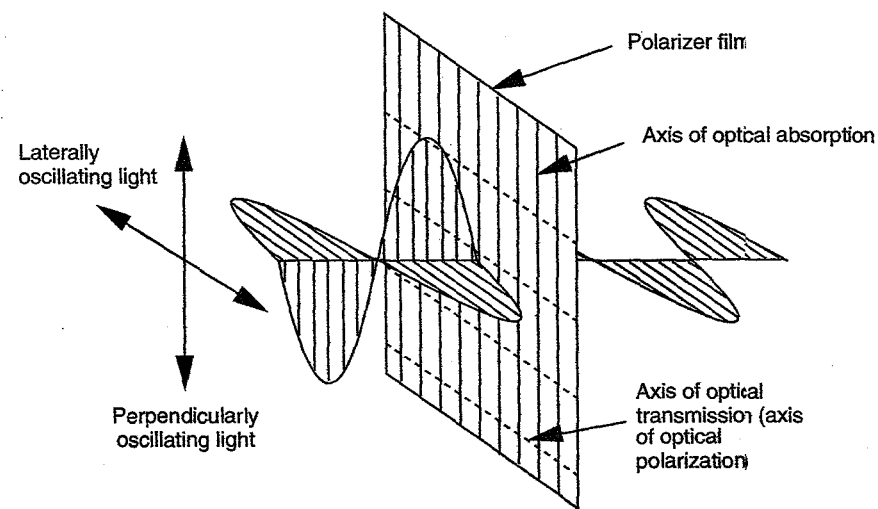


Figure 2.14 Light passing through a polarizer film

2.5 LIGHT TRANSMISSION AND LIQUID CRYSTAL MOLECULES

Because liquid crystal molecules contain rigid parts, they orient themselves as if they were crystals, with the long axes pointing in one direction and the short axes in other directions. In other words, the crystal-like property of liquid crystal molecules renders them immobile and serves to confine them in a small space. There is a large difference between the length of the liquid crystal's long axis and its short axis. Therefore, in a liquid crystal molecule there is a significant difference in electron density between the vertical axis and the horizontal axis. This means that an electron density anisotropy exists within a liquid crystal molecule.

For these reasons, a liquid crystal molecule exhibits an anisotropy in a variety of its physical constants, including refractive index, dielectric constant, magnetic susceptibility, and electric conductivity. Further, due to its shape, the liquid crystal molecule possesses an elastic modulus and a viscosity coefficient that are unique.

Many liquid crystal displays exploit the fact that the liquid crystal molecules have two types of refractive indices, according to the way the liquid crystal molecules are oriented; namely, a double refraction property, in order to control the way light passes through them.

Assume that when light passes through substances that have different refractive indices, the linearly polarized component, oscillating perpendicularly from the left, passes through a substance having a refractive index n_e greater than the refractive index of air. This is illustrated in Figure 2.15. Because the refractive index of this substance is greater than that of air, light propagates more slowly in the substance. Generally, substances such as solids and liquids

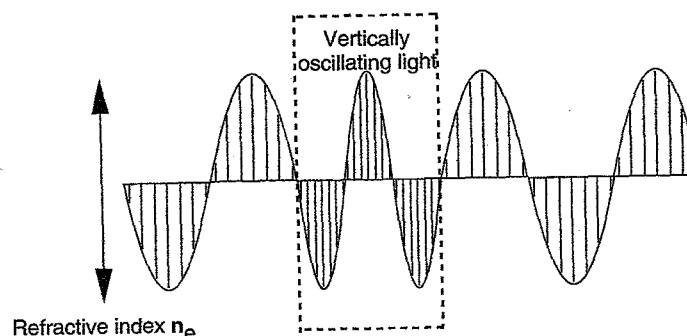


Figure 2.15 A vertically oscillating light component passing through a substance with refractive index n_e

that are denser than air contain more densely arrayed atoms, and consequently in these substances the electron density is higher. Because light encounters more electrons during its passage, its speed of propagation slows down. As a result, the light advances more slowly, causing the oscillation to become compressed, as shown in Figure 2.15. After emerging from the substance, the light passes through the air, as it was doing before it entered the substance, and returns to its original speed of propagation. Let us now consider the case where a light component, oscillating laterally from the left, passes through a substance having a different refractive index, say, n_o . As shown in Figure 2.16, the light propagates slowly in the substance, in a manner identical to that shown before.

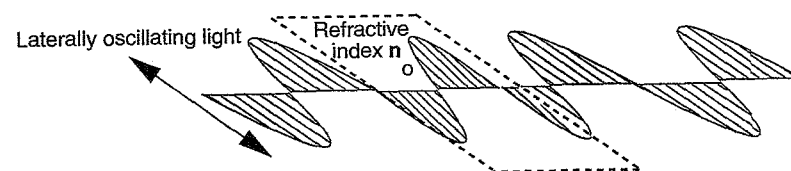


Figure 2.16 A laterally oscillating light component passing through a substance with refractive index n_o

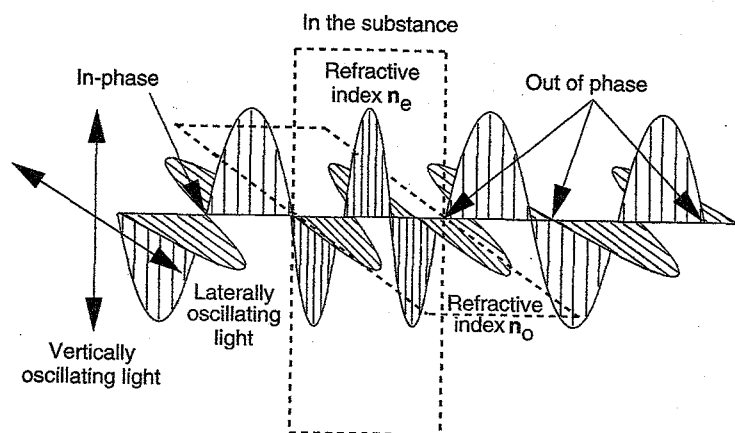
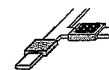


Figure 2.17 When vertically and laterally oscillating light components pass through a substance having a vertical refractive index n_e and a lateral refractive index n_o , these light components become out of phase with each other

Figure 2.17 shows a case where the two light components are superimposed, for which the refractive index of air is denoted as n_{air} , such that $n_e > n_o > n_{air}$. If, in a substance, the refractive index for the vertical component of light is different from that for the lateral component, then the light emerging from the substance exhibits a perpendicular oscillation phase different from its lateral oscillation phase (Figure 2.17). This phenomenon is referred to as "being out of phase."

As in the above example, liquid crystal molecules are a typical substance for which vertical and lateral refractive indices are different. A difference in electron density between the direction of the long axis for the liquid crystal molecules and the direction of the short axis produces a difference in the refractive index. The orientation of the liquid crystal molecule in the direction of the long axis is called the "director" (D). Let n_e denote the refractive index



in the D direction, and n_o the refractive index in a direction perpendicular to D. Let us now assume that linearly polarized light that oscillates at a certain angle with respect to D enters into the molecules from the left, as illustrated in Figure 2.18. In this case, the oscillation vector of the linearly polarized light propagates by being decomposed into the direction of the director (extraordinary light) and into a direction perpendicular to the director (ordinary light). When the linearly polarized light passes through the liquid crystal molecules, the decomposed components (the

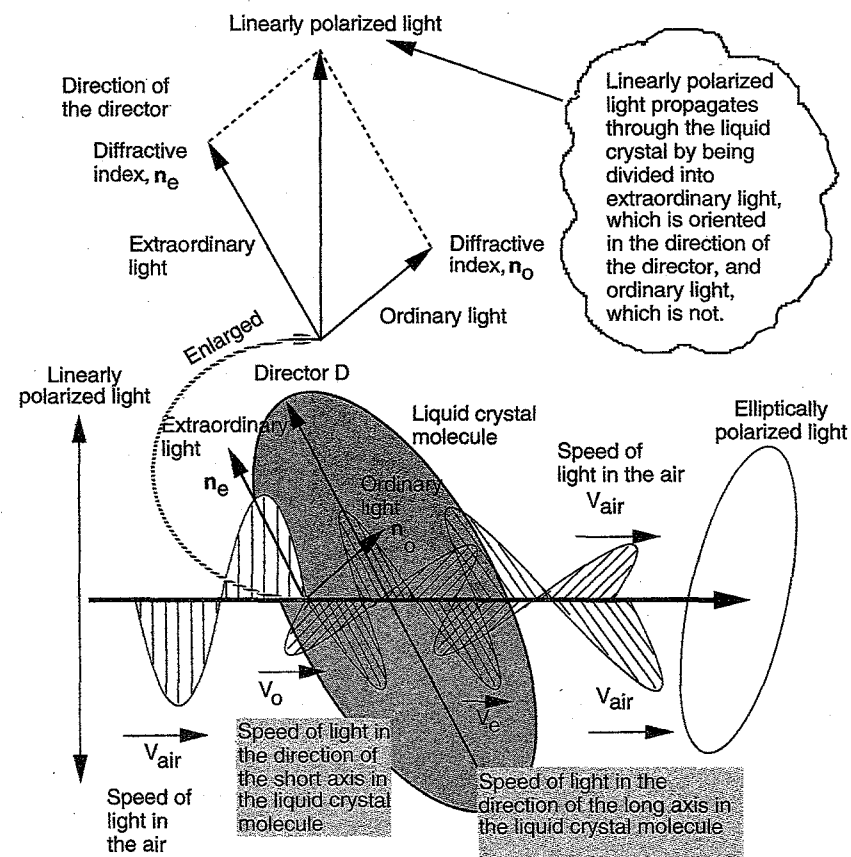


Figure 2.18 Light passing through a liquid crystal molecule

extraordinary and ordinary rays) propagate with refractive indices n_e and n_o , respectively. Therefore, as the foregoing indicates, the components of the ray of light undergo a change in the rate of propagation. Specifically, the rates of propagation are related in $v_{air} > v_o > v_e$ order, in inverse proportion to the refractive indices ($n_e > n_o > n_{air}$). Therefore, when the light exits the molecule, it exhibits a phase shift due to the differences in the refractive index. The rate of propagation of the light reverts to the original velocity, v_{air} . Furthermore, the light continues to propagate at the same velocity, v_{air} , with its vertical and lateral components out of phase. If the out-of-phase light components are recombined, the direction of the vibration vector rotates as a function of time. Because all incoming light is decomposed into different components, the components remain out of phase while traveling at the same speed. Therefore, the vibration vector traces an elliptic curve. Whether the light rotates clockwise or counterclockwise depends on the symmetry of the molecules.

It should be noted that the incident light was linearly polarized using a polarizer film. Unlike a laser beam, the polarized light is not collimated with respect to the phase. Therefore, even though each vector rotates on exiting the molecule, when the light enters the molecule it contains many light components with different phases. When these phases are averaged, the result is a simple ellipse and is called elliptic polarization.

As the foregoing indicates, incident linearly polarized light is changed into elliptically polarized light by the double refraction of the liquid crystal molecules. If a polarizer is placed at the exit, the result is the transmission of polarized light from the elliptically polarized light, if the axis of



the light ray coincides with the polarizer. Although this results in an attenuation of light, it produces a linear polarization whose angle is different from the incident angle. Many LCDs are designed to exploit this phenomenon, which is referred to as the birefringence mode.

2.6 ARRANGEMENT OF LIQUID CRYSTAL MOLECULES

To control polarization by applying an electric field to liquid crystals, first of all it is necessary to hold the liquid crystals between two glass substrates so that the liquid crystals form a regular pattern. The extent to which the liquid crystals are oriented when they are sandwiched between glass substrates holds the key to the quality of the resulting LCD.

What criteria are used to determine the particular arrangement to be employed? An orientation is influenced by the geometric structure of liquid crystal molecules and the phase of liquid crystals that arises due to environmental conditions such as temperature and concentration. As noted previously, nematic and smectic states are called phases. Different phases, obviously, contain different liquid crystal orientations. Therefore, the first task is to choose the phase to be used. Another orientation-determining factor is the interaction between the liquid crystal molecules and the substrate. If the bond between the substrate and the liquid crystal molecules is strong, the liquid crystal molecules are liable to undergo twisting and become oriented at specific angles. Therefore, liquid crystal orientation is determined by the phase of liquid crystals, the structure of liquid crystal molecules, and the interaction between the molecules and the substrate.

Figure 2.19 shows a typical example of such an orientation. In a homeotropic orientation, all liquid crystal molecules are oriented perpendicular to the substrate. In a homogenous orientation, all liquid crystal molecules are parallel to the substrate and oriented in the same way. In the focal conic orientation, the liquid crystal molecules form a helix around an axis, and the axis (called the helical axis) is parallel to the substrate. Within the plane, the liquid crystal molecules in a focal conic orientation are oriented in different directions. Finally, in a twisted orientation, all liquid crystal molecules are parallel to the substrate, in such a way that the direction of the orientation is twisted 90° between substrates.

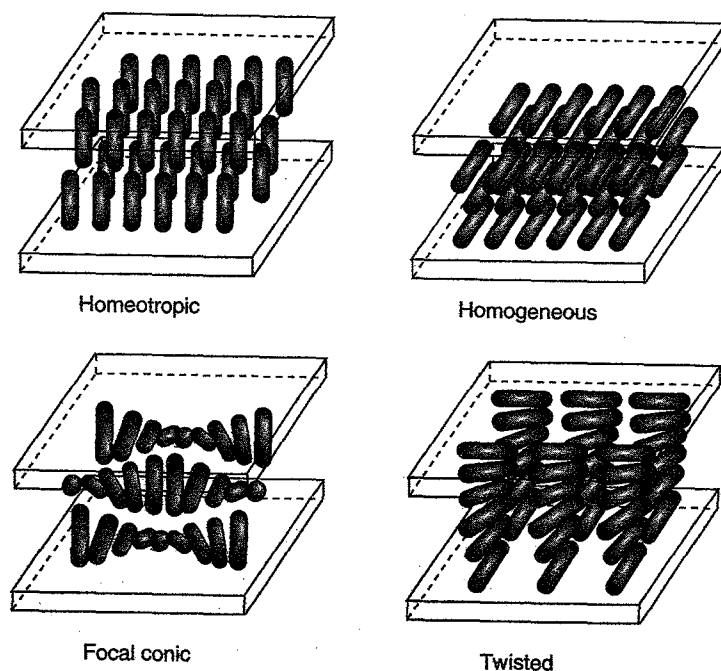


Figure 2.19 Arrangement (alignment) of liquid crystals



To create such a twisted orientation, it is necessary to form a film called the orientation layer in order to align the liquid crystal molecules.

In the case of homogeneous orientation, a commonly used technique for aligning liquid crystal molecules is the rubbing technique. The following is a brief description of how the rubbing technique works. For forming an orientation layer, a thin film, such as polyimide, is applied to the surface of a substrate coated with a transparent electrode (ITO) that drives the display. The thickness of the layer is 500 Å. Next, a roller made with soft cloth is used to rub the surface of the polyimide thin-film in one direction in order to align the molecules that comprise the base-layer polymer. When LC cells are assembled, the liquid crystal molecules sense the way the base-layer polymer molecules are oriented, and the interaction (attraction and repulsion) between the base polymer molecules and the liquid crystal molecules causes the liquid crystal molecules to be aligned the same way the base polymer molecules are oriented. At present, most orientation layers are polyimide layers. In fact, there are no materials that can outperform the polyimide thin-film in terms of the hardness of molecules, transparency, and the ability to withstand heat (250°C) during the manufacturing process.

In the early stages of development, the technique of forming an orientation layer by tilted-angle vapor deposition was investigated. This technique involves heating and vaporizing an inorganic substance, such as silica, in a vacuum, and directing the inorganic vapor to the substrate from an angle, so as to form (by tilted vapor deposition) a thin film of the inorganic substance on the substrate, thus producing geometric grooves on the substrate.

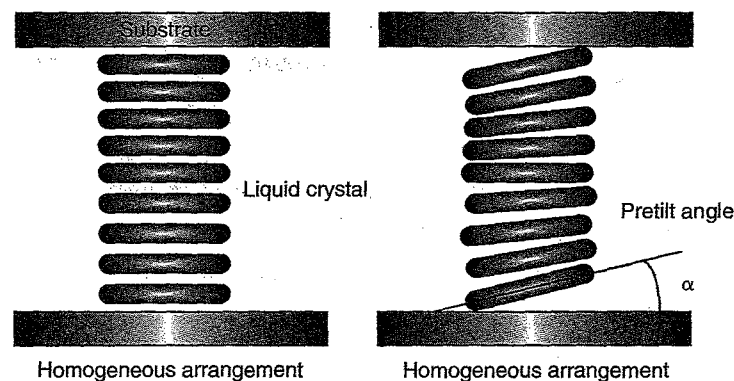


Figure 2.20 Pretilting the liquid crystal molecules

An important requirement in these alignment techniques is that, as illustrated in Figure 2.20, the angle between the long axis of the liquid crystal and the substrate surface be adjusted to a specific angle (pretilt angle, α). The use of an alignment agent that produces a chemical bond with the substrate, such as a silane-coupling agent, is well known.

2.7 LIQUID CRYSTAL OPERATING MODES

Certain isotropic molecules undergo a change in their molecular electron density when the molecules are subjected to an electric field, and acquire a uniaxial crystal property. For example, the liquid nitrobenzene exhibits a birefringence when subjected to an electric field. An example of a phenomenon (electro-optical effect) in which a substance exhibits an optical anisotropy due to an electric field is the Kerr effect.

Liquid crystal molecules possess anisotropic properties, such as refractive index, dielectric constant, magnetic susceptibility, and conductivity. They can also exhibit



singular properties of the modulus of elasticity and viscosity. By exploiting these properties and a type of Kerr effect, it is possible to use the electric field to re-align (transition) the liquid crystal molecules so as to control the way they polarize light. Such a transition of liquid crystal molecules is called the Freedericksz transition. LCDs make an extensive use of the Freedericksz transition. The following is a description of the LC operating modes using various electro-optical effects, including the Kerr effect.

The principal LC operating modes are as follows:

- (1) TN (twisted nematic) mode
- (2) STN (super-twisted nematic) mode
- (3) Ferroelectric liquid crystal (FLC) mode
- (4) Birefringence (ECB) mode
- (5) Guest-host (GH) mode
- (6) Dynamic scattering (DS) mode
- (7) Phase change (PC) mode
- (8) Thermo-optic mode, thermo-electro-optic mode

In what follows, we will discuss the representative modes, the TN mode, the STN mode, and the FLC mode, by tracing the history of development of color TFT technology.

2.7.1 TN Mode

The TN mode is historically one of the oldest operating modes, and it is still the dominant method. An orientation layer composed of polyimide is applied to the surfaces of two glass substrates that are equipped with transparent electrodes, and the layer is rubbed. Next, spacers about 5-8 μm in size are sprayed onto the substrates, a sealing agent is applied to the edges of the display unit, and a panel is assembled by gluing together the two glass substrates coated with transparent electrodes. When nematic liquid

crystals are injected into the gap between the substrates in the panel, they adopt a 90° twisted orientation with respect to the substance, and the structure shown in Figure 2.21 results. When polarizer films are fixed onto the exterior surfaces of the two glass substrates so that the polarization axes (transmission axes) of the substrates are at 90° to each other, the result is a TN liquid crystal panel. Let us now examine the way light is transmitted through this panel, by taking the panel apart in functional terms.

In the TN liquid crystal, rotation of the polarization axis of linear polarized light occurs. This phenomenon, called "optical rotation," is caused by two properties of the liquid crystal: the ability to rotate light and the ability to produce a birefringence effect.

First, let us discuss the optical rotation. When light enters the panel from the top and passes through the first

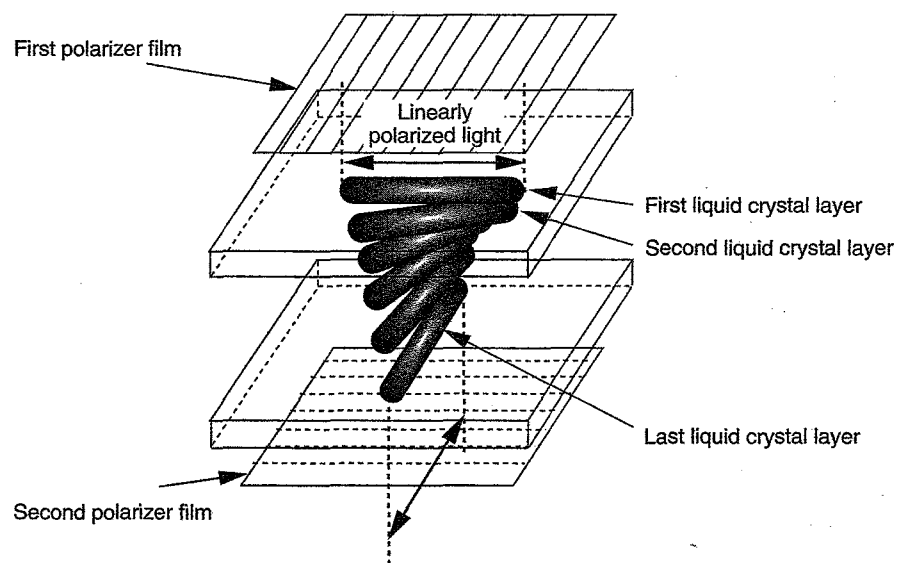
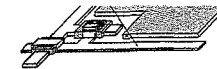


Figure 2.21 Structure of a twisted nematic liquid crystal panel

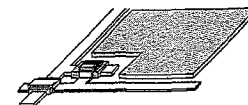


polarizer film, as illustrated in Figure 2.21, only the light that has the electric field component that oscillates in a direction parallel to the short axis of iodine molecules is transmitted. Because the long axis of the linearly polarized light that has passed through the polarizer film and the long axis of liquid crystal molecules coincide, the linearly polarized light enters the panel in a direction parallel to the director (long axis) of the liquid crystal molecules. The light passing through the first molecular layer rotates along the molecules and enters the second molecular layer. The net effect is that the angle of the linearly polarized light twists in an angle equal to the angle by which the molecular layer is twisted. When this phenomenon occurs repeatedly and the light reaches the bottom molecular layer, the polarization axis of the linearly polarized light has rotated an amount equal to the total amount of the twist of the molecules. This phenomenon is referred to as "optical rotation." Because the phase becomes shifted by 90°, however, the helical pitch of the liquid crystals (the period of the helical structure: $p = d \cdot 2\pi / \Theta$, where Θ denotes the twist angle) of the liquid crystal must be longer than the wavelength of the incident light. This condition (Equation 2.1) is referred to as Mauguin's condition (limit).

$$\Delta n p = \Delta n d \cdot 2\pi / \Theta > \lambda \quad (2.1)$$

where Δn is the retardation of the light, p is the phase, d is the cell gap, and λ is the wavelength of incident light.

If Mauguin's condition is not satisfied, either the light scatters or light of a specific wavelength is reflected. This causes a coloration, and can create the problem in which



an image produces different colors depending upon the angle from which it is viewed. In the case of an actual TN liquid crystal, if Δn is 0.08-0.10 and the cell gap for the liquid crystal is $5\text{ }\mu\text{m}$, the helical pitch p ($=d \cdot 2\pi/\Theta$, $\Theta=\pi/2$) is $20\text{ }\mu\text{m}$, and $\Delta n p$ is greater than the wavelength λ of visible light ($0.38\text{ }\mu\text{m}$ - $0.78\text{ }\mu\text{m}$ ($= 380\text{ nm}$ - 780 nm)) by a factor of 2.5 to 5. Thus, Mauguin's condition is satisfied.

Let us now turn to birefringence. The rotation of the axis of polarization due to birefringence can be explained in terms of the theory of elliptic polarization (Figure 2.18) for the transmission of light through liquid crystal molecules, which was discussed in Section 2.5. The optical properties of liquid crystals must be understood in terms of the overall behavior of the liquid crystal layer rather than in terms of a single molecule. Since the liquid crystal layer is twisted by 90° between the top molecule and the bottom molecule, no matter at what angle linearly polarized light enters the panel, there is always a liquid crystal layer that possesses a certain angle with respect to the incident linearly polarized light. Therefore, as illustrated in Figure 2.18, in the light passing through the liquid crystal layer, a phase difference occurs between extraordinary light and ordinary light, and this produces an elliptic polarization. What will happen if exactly 90° of phase difference occurs when the incident linearly polarized light has passed through the liquid crystal layer? The answer is, a linear polarization with exactly 90° twist results, as illustrated in Figure 2.22. Therefore, the light rotates 90° , as if it behaved in tandem with the twisting of the liquid crystal molecule. Thus, a TN liquid crystal produces the effect of a 90° phase difference between extraordinary light and ordinary light, as these light components pass through the

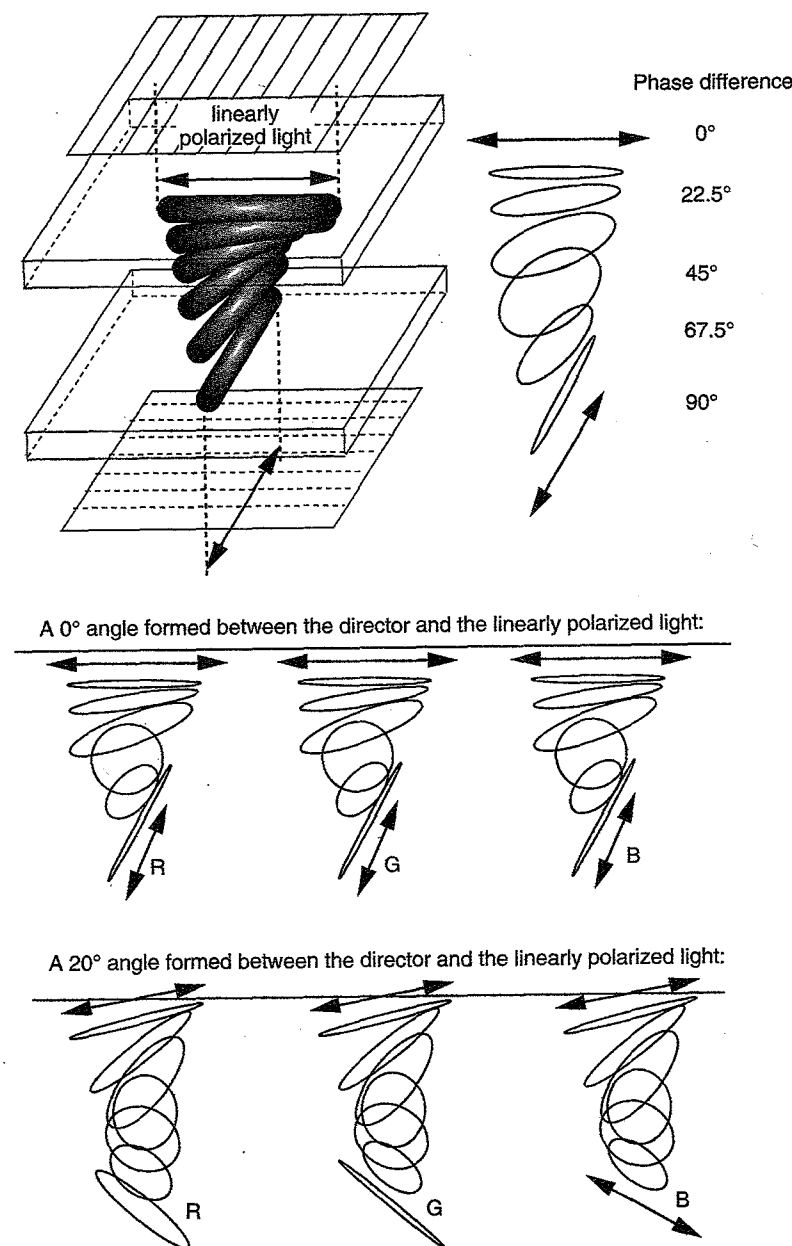
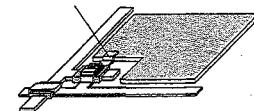


Figure 2.22 Phase misalignment between the linearly polarized light rays that pass through TN liquid crystals

liquid crystal layer. In other words, the TN liquid crystal is a panel in which the thickness of liquid crystals is adjusted by design so as to produce a 90° phase difference. The light transmittance of the TN liquid crystal panel, which is designed by taking the birefringence effect (phase-shift) into consideration, can be expressed as a retardation function, which is the product, $\Delta n d$, of the difference in refractive index between the long and short axes of liquid crystal (refractive index anisotropy) and the thickness, d , of the liquid crystal cell. Therefore, it is possible to design a retardation by adjusting the liquid crystal refractive index anisotropy and the thickness of the liquid crystal cell, and by exploiting the optical rotation effect, so that a phase shift of exactly 90° occurs. Thus, the rotation of the axis of polarization in linearly polarized light occurs as an interaction between optical rotation and birefringence.

Why then, is it necessary in a liquid crystal panel, to ensure that the direction of the incident linearly polarized light agrees with the director for liquid crystal molecules? According to the principle of birefringence (phase difference) discussed above, the director for liquid crystal molecules occurs in a wide range of distribution, from 0° to 90° . Therefore, no matter at what angle light enters the panel, there always is a liquid crystal molecule that has one of the angles 0° - 90° . Therefore, when linearly polarized light enters the panel, an optical rotation occurs for any incident angle. However, since white light, containing light components of various wavelengths, rather than monochrome light, passes through the actual TN liquid crystal, the problem of wavelength dispersion (optical rotation dispersion) can occur. In actual examples of TN liquid crystals, there are cases in which Mauguin's condition is not satisfied at



short wavelengths. In such a wavelength region, a sufficient optical rotation does not occur, and optical rotation is overshadowed by birefringence. As a result, TN liquid crystals can exhibit a wavelength dependency. In other words, the linearly polarized light components of certain wavelengths, when passing through a liquid crystal layer, become misaligned from linear polarization with a 90° twist, and become elliptically polarized. To minimize this effect as much as possible, it is necessary to ensure that the linearly polarized light and the director for the liquid crystal molecules for the first incident layer be in agreement, as illustrated in Figure 2.22.

A few words on wavelength dispersion may be in order. If the top and bottom polarizer films are positioned as cross Nicols (staggered by 90°), the light transmittance of the TN liquid crystal panel, when no voltage is applied, can be expressed by Equation 2.2, assuming a twist angle Θ . In Equation 2.2, when u^2 is 3, 15, 35, 63, ..., the transmittance I is 100%. Under this condition, the incident linearly polarized light is turned exactly 90° , and it is output as linearly polarized light that does not contain any elliptic polarization.

$$I = 1 - \left[\sin^2 \left(\Theta \sqrt{1 + u^2} \right) \right] / (1 + u^2)$$

$$\text{where } u = \frac{\Delta n d}{\lambda} \cdot \frac{\pi}{\Theta} \quad (2.2)$$

In Equation 2.2, if $\Delta n d$ is fixed at $0.48 \mu\text{m}$, as in an actual TN mode, the wavelength dependency of light transmittance due to the twist angle is shown in Figure 2.23. If the twist angle is less than 90° , as in TN liquid crystals, except for the two wavelength regions at the edges,

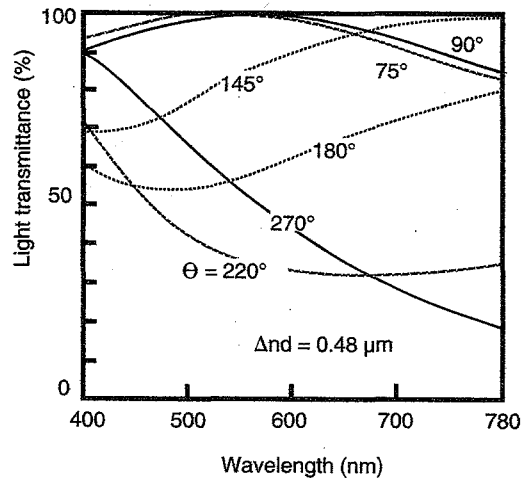


Figure 2.23 Wavelength dependency of light transmittance due to the twist angle

hardly any wavelength dependency occurs. However, as the twist angle increases, so does the wavelength dependency of light transmittance. Thus, if the twist angle is as large as 180°-270°, as in the STN mode, a large wavelength dependency results.

On the other hand, for the TN mode, in which Θ is $\pi/2$ ($=90^\circ$), the light transmittance, I , can be expressed by Equation 2.3:

$$I = 1 - \left[\sin^2 \left(\frac{\pi}{2} \sqrt{1 + (2\Delta nd/\lambda)^2} \right) \right] / [1 + (2\Delta nd/\lambda)^2] \quad (2.3)$$

Thus, the light transmittance I is a function of Δnd and depends only on the retardation and the wavelength. In this case, the wavelength dependency of light transmittance due to retardation is shown in Figure 2.24. The larger the retardation, Δnd , the smaller the wavelength dependency. However, because a large cell gap results in a

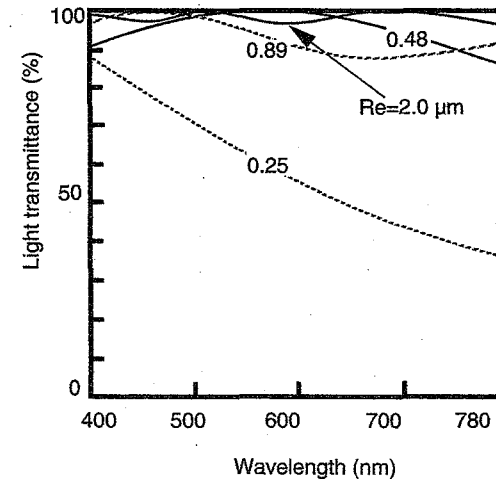
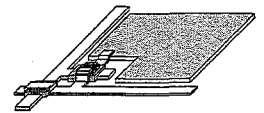


Figure 2.24 Wavelength dependency of light transmittance due to retardation

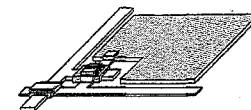
reduced response speed, in actual liquid crystals the retardation is designed to be in the 0.5 - 1.3 μm range.

Thus, in actual liquid crystal panels, a wavelength dispersion occurs in the rotation (phase misalignment) of the axis of polarization due to birefringence. As described above, although the rotation of the axis of polarization is caused by the birefringence inherent in liquid crystals, the effect of wavelength dispersion makes the actual behavior of polarization axis rotation complex. Actual liquid crystal panels are designed so that the linearly polarized light passing through the liquid crystal layers emerges from the liquid crystal layers after undergoing a 90° twist relative to the incident angle.

The linearly polarized light passing through the liquid crystal layers will pass through the second polarizer film. However, since the light matches the linearly polarized light transmission angle of the polarizer film, the linearly

polarized light emerging from the liquid crystal layers is totally transmitted "as is." However, because the polarizer film transmits only specific linearly polarized light components from the incoming light, the light intensity is reduced to less than 50% of the initial value.

When an electric field is applied to the liquid crystal layers, the anisotropy of the dielectric constant of the liquid crystal molecules, i.e., the electron bias that exists in the molecules, causes the long axis of the liquid crystal molecules to turn parallel to the direction of the electric field. This, in turn, causes the liquid crystal molecules to line up perpendicularly to the substrates. Let us assume that incoming light strikes the liquid crystal panel from the top under these conditions. As illustrated in Figure 2.25, when the light passes through the first polarizer film, as discussed previously, only the components that oscillate in a direction parallel to the short axis of the iodine molecules are transmitted. Because the linearly polarized light and the long axis of the liquid crystal molecules are perpendicular to each other, the linearly polarized light enters perpendicular to the long axis of liquid crystal molecules. The light that has passed through the first liquid crystal layer becomes optically uniform because the directors of liquid crystals are more or less aligned, and proceeds to the second liquid crystal layer without undergoing any change. While maintaining this state, the linearly polarized light exits the liquid crystal layer, remaining parallel to the incident direction. Next, the linearly polarized light attempts to pass through the second polarizer film. However, since the polarizer film is twisted by 90° to the incoming polarizer, the linearly polarized light emerging from the liquid crystal layer is unable to pass through the second polarizer



film. This state, in which light is transmitted in the absence of an electric field and is blocked in the presence of a field, is referred to as the "normally white mode." On the other hand, if the first and second polarizer films are arranged in parallel, the light is blocked in the absence of a voltage but is transmitted with the voltage applied. This state is referred to as the "normally black mode." The operating mode is determined by the way the polarizer films are arranged.

In this way, the transmission of light can be regulated through the application of an electric field (voltage). In actuality, when a low voltage is applied to the liquid crystal layers, the liquid crystal molecules remain in the state shown in Figure 2.21. However, when the voltage exceeds a certain value, the liquid crystal molecules become activated. This voltage is called the critical voltage. When a voltage greater than the critical voltage is applied, the liquid crystals realign themselves, as illustrated in Figure 2.25. Figure 2.26 depicts this condition by plotting the voltage on the horizontal axis and the tilt angle at the center of the liquid crystal layer on the vertical axis. Even when a voltage slightly greater than the critical voltage is applied, no change in transmittance occurs. A change in transmittance occurs suddenly when the voltage is further increased, and the realignment of liquid crystals in excess of a certain tilt angle is induced. The voltage at which an optical change, such as a change in transmittance, occurs is referred to as a threshold voltage.

It should be noted that only an AC electric field is applied to the LC panel. The liquid crystal layer is a liquid solution, and is also an insulator. Therefore, since it does not conduct current, the orientation of the liquid crystal

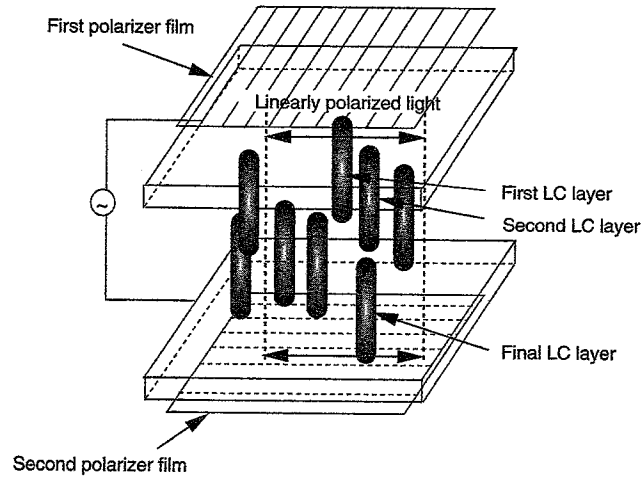


Figure 2.25 Structure of a TN LC panel with an electric field applied

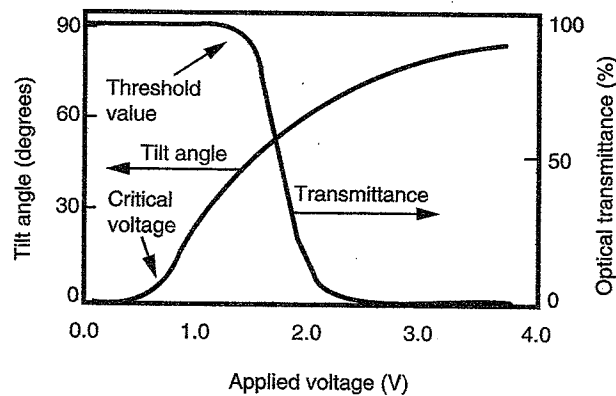
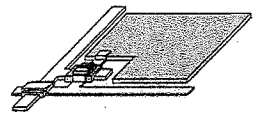


Figure 2.26 Electric potential dependency of the tilt angle and the transmittance in a twisted nematic LC panel

molecules can be changed by an AC electric field. This is the reason why the LC panel consumes very little electrical power in producing a display effect. Thus, a significant advantage of LC panels is their low power consumption compared with other display devices.



As shown in Figure 2.27, in the past, TN LC panels were mostly used for displaying the time in watches, with a response time of 500 ms. Subsequently, decreases in the cell gap and improvements in techniques for reducing the viscosity of LC materials spurred rapid advances in technology, to the point where these panels find use in scroll displays with a response time of 200 ms, and in TFT LC television sets with a response time of 70-100 ms. They are now used as TFT LC displays with a 20-50 ms response time with no image retention.

For driving a TN LC panel, the ratio of the optical transmittance of a white display to the baseline optical transmittance of a black display is called the contrast ratio. For driving a TN liquid crystal, the optical transmittance before applying a voltage is 100%, as shown in Figure 2.26. The transmittance drops to less than 1% after a voltage is

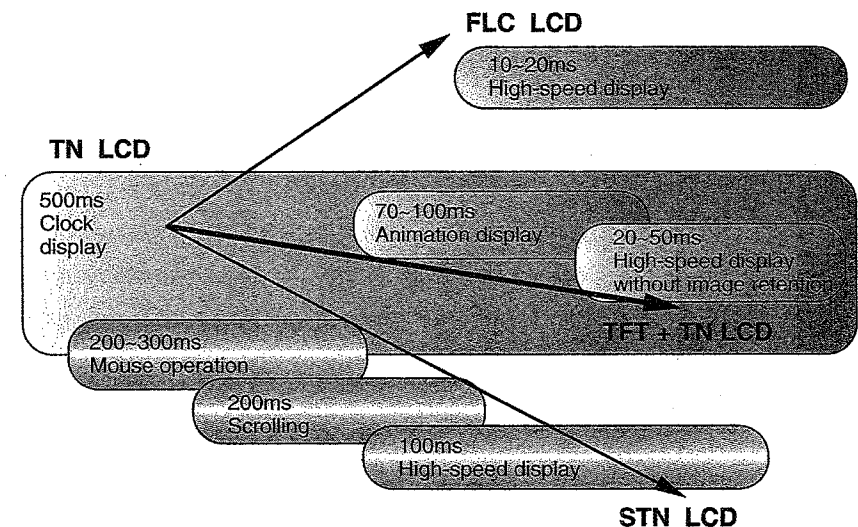


Figure 2.27 Changes in liquid crystal display and the drive speed

applied, thus achieving a high contrast ratio. As another consideration, for a TN LC panel to be used as a display device for a TV set or a personal computer monitor, and as an animation display, the response speed of the liquid crystal needs to be fast. To solve this problem, improvements in LC materials have been accomplished.

2.7.2 STN Mode

(1) STN Mode

In a simple or passive matrix display, it is desirable that changes in optical transmittance occur rapidly around the threshold value. The faster the rate of change, the greater the change in the transmittance for the LC panel as a function of the realignment of liquid crystal molecules, and the clearer the resulting picture. Because the rate of change in transmittance in the TN mode is gradual, as shown in Figure 2.26, there has been a great need for improving the threshold characteristics. This led to the development of a fundamental change in the operating mode, from the TN mode to the STN mode (super-twisted nematic mode).

Adding some chiral nematic liquid crystals and chiral compounds to nematic liquid crystals causes the nematic liquid crystals to assume a helical structure, as shown in Figure 2.28. Figure 2.29 shows the angles and constants formed by the various components of the resulting panel. Of these constants, the angle by which the helix rotates, or the twist angle, is a critical factor. The threshold value for the liquid crystal can be improved significantly by setting the twist angle, Θ , to 180° - 270° . Figure 2.30 shows the voltage dependency of the tilt angle χ , which is the angle formed by the substrate and the liquid crystal. The figure

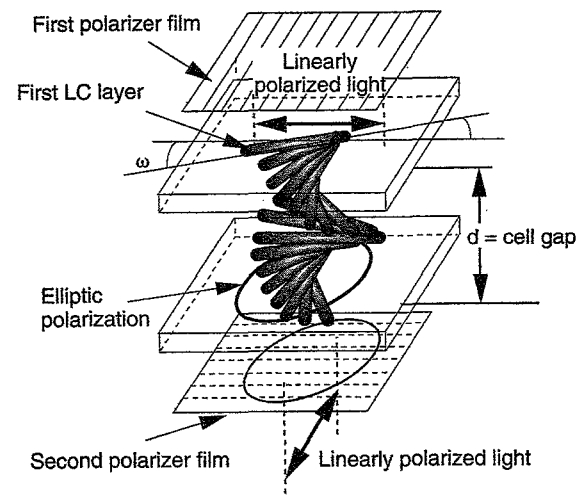
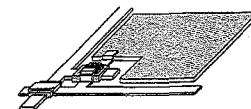


Figure 2.28 Structure of an STN LC panel

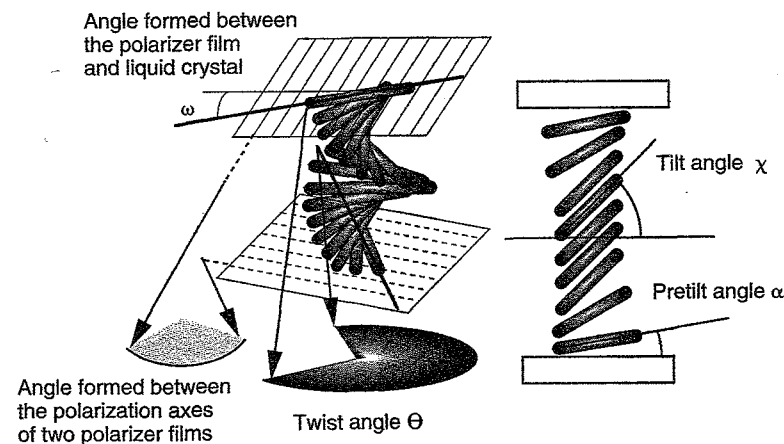


Figure 2.29 Components of an STN LC panel and their meanings

indicates that when the twist angle Θ of the helix is 240° - 270° , the tilt angle rises sharply in the vicinity of the threshold value (threshold characteristics). This operating mode is referred to as the STN mode.

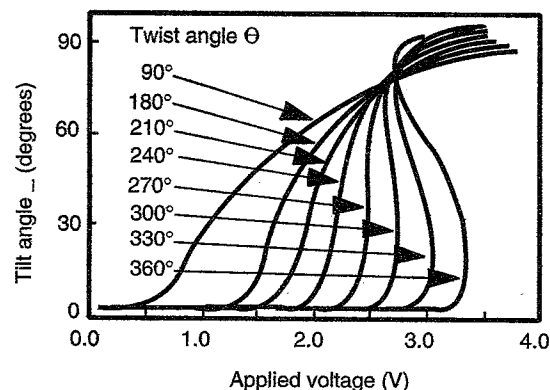
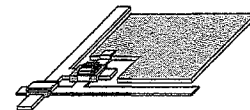


Figure 2.30 Threshold characteristics of an STN LC panel

As in the case of the TN mode, for making an STN LC panel an orientation layer is applied to the electrodes on the substrate, and the amount of the chiral compound added and the cell gap are adjusted so that the liquid crystals are twisted by 240° - 270° . Specifically, the desirable ratio between cell gap d and twist pitch p is designed so that $d/p = 0.6$ - 0.9 . When the 270° twist angle is used, care should be taken to ensure that the range of d/p values is sufficiently large so that no patches of 90° twist angles (twist domains) exist that are one-half smaller in pitch. The difference between the upper and lower bounds on d/p values is referred to as the d/p margin, and the larger the d/p margin for an LC display, the more stable is the display.

The term "disclination" is a general term encompassing the defects that are caused by twisting. A defect which is caused when a crystal moves parallel to its crystal lattice is usually called a dislocation. However, a disclination, which is a defect attributable to twisting, is distinguished from a dislocation. A significant cause of disclination is the viscoelasticity of the liquid crystal. As shown in Figure



2.31, the viscoelasticity of a liquid crystal is determined by three elasticity constants: splay (K_{11}), twist (K_{22}), and bend (K_{33}). This force makes the liquid crystal a continuous fluid, and provides a driving force such that after the liquid crystal is driven and the voltage is removed, the liquid crystal molecules regain their original state. On the other hand, any imbalance that is produced as a result of the application of the driving force leads to the occurrence of a disclination. Therefore, in an LC panel it is important to provide an adequate d/p margin in order to prevent disclination.

To prevent a disclination in an STN panel, the angle α formed by the liquid crystal molecule layer and the substrate (pretilt angle) must be 1 - 2° larger than the pretilt angle for a TN liquid crystal, so that it is in the range of 4 - 15° . This is necessary in order to prevent the formation of a domain (disclination) due to a decrease in the twist angle Θ .

For the reasons indicated above, the twist angle Θ is set to 180° - 270° ; pretilt angle α to 4 - 8° ; cell gap d to 5 - $8 \mu\text{m}$; the d/p margin to 0.6 - 0.9 ; and the cell gap uniformity to $0.1 \mu\text{m}$. After a stable liquid crystal cell is assembled, two polarizer films are attached. While adjusting the contrast so that it is at the maximum, the angle β formed by the polarization axes of the two polarizer films is adjusted to

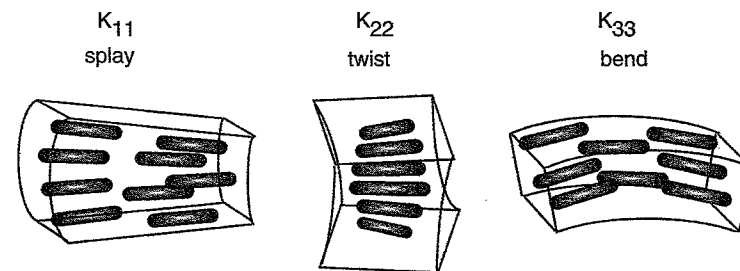


Figure 2.31 Meanings of elastic coefficients

an angle slightly less than a right angle. At the same time, polarizer film orientation is optimized by setting an angle ω formed by the polarization axes of the polarizer films and the directors of the top and bottom liquid crystal layers. The result is a finished STN LC panel.

When ordinary light enters the LC panel from the top, the situation shown in Figure 2.28 results. First, in ordinary light, the light whose polarization axis and the electric field components coincide passes through the first polarizer film and becomes linearly polarized light. The polarizer film is placed so that the direction of the linearly polarized light forms an angle ω relative to the director (long axis) of the liquid crystal molecule. As was shown in Figure 2.18, the birefringence of the liquid crystal molecule turns this light into elliptically polarized light at the outlet. The second polarizer film allows the passage of only the linearly polarized light, the component of the elliptically polarized light that is oriented in the direction of the transmission axis of the polarizer film.

When a voltage higher than the threshold value is applied to the LC panel, the liquid crystal molecules reorient themselves perpendicularly to the substrate, as in the case of the TN LC panel (see Figure 2.32). Therefore, the linearly polarized light that has passed through the first polarizer film is unable to pass through the second polarizer film. This condition, in which light is transmitted in the absence of a voltage, is the normally white mode.

The "blue mode" refers to an STN-mode display under normally-black-mode conditions, in which the angle of the polarizer films is adjusted to achieve the highest contrast. The blue mode is based on a color change between blue and light yellow to a transparent color (non-display/

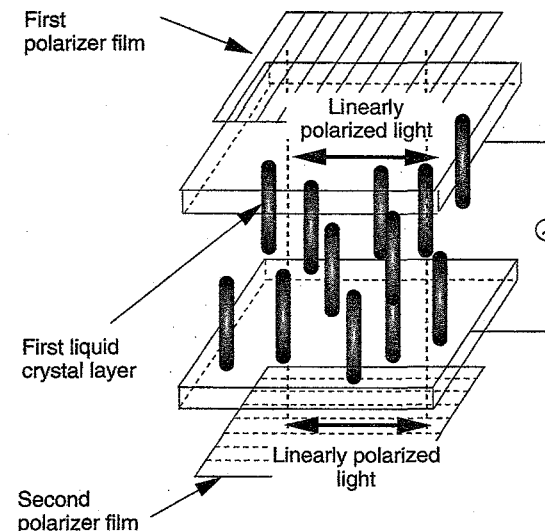
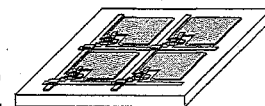


Figure 2.32 Operation of an STN liquid crystal panel

display). On the other hand, the "yellow mode" refers to a contrast enhancement technique which is based on a color change between yellow-green/dark blue to black (non-display/display).

The "optical interference" mode (OMI) refers to the technique of suppressing the colorization in the yellow mode by reducing the retardation (the product of refractive index anisotropy and the thickness of the liquid crystal layer — more on this later) from $0.87 \mu\text{m}$ to approximately $0.6 \mu\text{m}$.

(2) D-STN, F-STN Modes

The use of the birefringence (elliptic polarization) of liquid crystal molecules suffers from the drawback of colorization due to the wavelength dependency of the refractive index. To solve this problem, the D-STN (double super-twisted nematic) mode has been developed, in which an LC panel

containing a helix of the opposite orientation is placed in front of the second polarizer film. This technique later gave way to the F-STN (film super-twisted nematic) mode, in which the requisite compensation is achieved through the use of a phase-difference film that has one birefringence and that is as effective as two STN compensation panels. The following compares the two modes with reference to Figure 2.33.

When ordinary light enters an STN LC panel from the top, the light that has passed through the first polarizer film becomes a linearly polarized light ray whose direction forms an angle with the director (long axis) of the liquid crystal molecules. Therefore, as was illustrated in Figure 2.28, the birefringence of the liquid crystal molecules turns this light into an elliptically polarized ray at the outlet. The

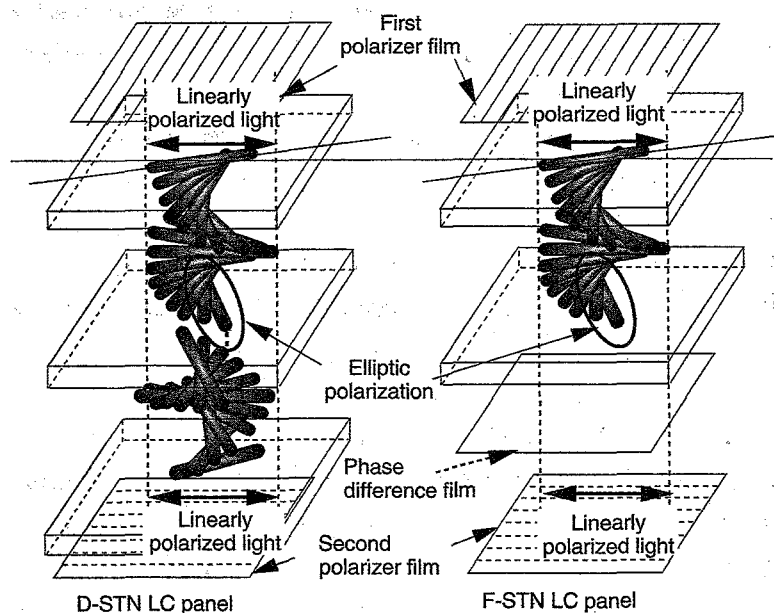
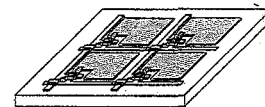


Figure 2.33 Driving principles for D-STN and F-STN LC panels



extent of the phase misalignment is determined by the retardation $\Delta n d$, which is the product of Δn ($= n_e - n_o$: refractive index anisotropy), which is the difference between the long-axis refractive index, n_e , and the short-axis refractive index, n_o , and the thickness (cell gap), d , of the liquid crystal layer. Because the refractive index anisotropy (Δn) is determined by the type of liquid crystal material used, it cannot be increased arbitrarily. A large cell gap (d), on the other hand, suffers from the drawback of a slow liquid crystal response time. Therefore, as in the case of a TN LC panel, $\Delta n d$ should be confined to a value 0.5–0.3 μm .

It should be noted, however, that the phase misalignment depends on the wavelength, as well as being a function of retardation $\Delta n d$, as indicated by the variable for the sin function in Equation 2.4 (which is obtained by substituting u into Equation 2.2).

$$I = 1 - \left[\sin^2 \left(\sqrt{\Theta^2 + \left(\pi \cdot \frac{\Delta n d}{\lambda} \right)^2} \right) \right] / \left[1 + \left(\frac{\pi}{\Theta} \cdot \frac{\Delta n d}{\lambda} \right)^2 \right] \quad (2.4)$$

This means that, as shown in Figure 2.34, the primary color components, designated RGB in the figure, have different extents of phase misalignment, or different shapes of elliptic polarization. Therefore, because these different wavelengths pass through the second polarizer film in different amounts, the result is a coloration.

On the other hand, because the STN liquid crystal has a helical structure, some of the linearly polarized light does not undergo an optical rotation. Although normally retardation R_e refers to the value $\Delta n d$, strictly speaking, it is expressed as shown in Equation 2.5. Thus, in addition to the product $\Delta n d$ of the refractive index anisotropy and the

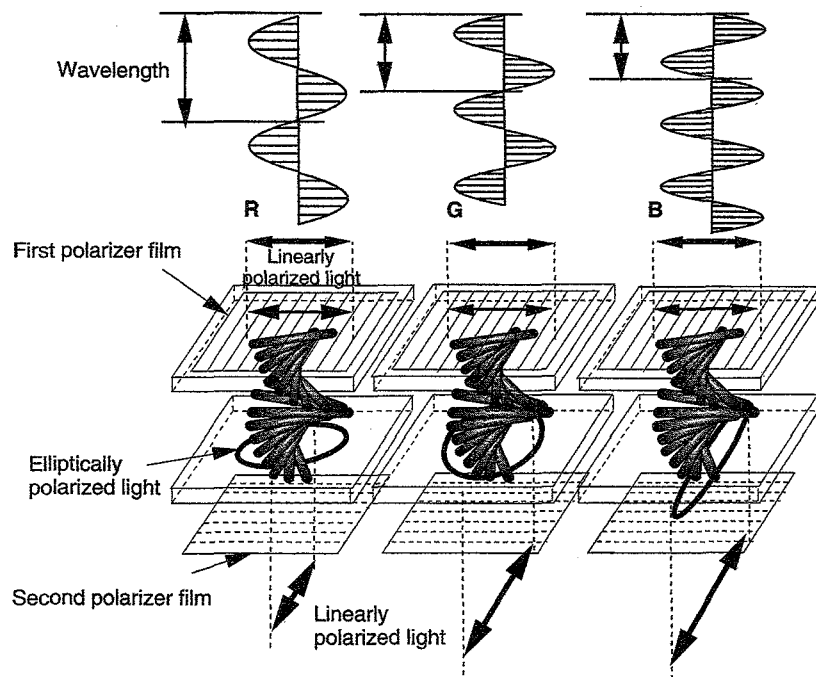


Figure 2.34 Wavelength dependency of birefringence

thickness of the liquid crystal layer, a retardation due purely to the twist angle Θ exists.

$$Re = \sqrt{\Theta^2 + \left(\pi \cdot \frac{\Delta n d}{\lambda} \right)^2} \quad (2.5)$$

The effect due to the Θ term is referred to as an optical rotation. In the case of an STN liquid crystal, typically $\Delta n d$ is $0.9 \mu\text{m}$ and $\Theta = 3\pi/2$. Therefore, if λ is $0.5 \mu\text{m}$, the retardation term $(\Delta n d \cdot \pi/2)^2$, which relates to the birefringence inherent in the liquid crystal, and the retardation term Θ^2 , which relates to the optical rotation due to twisting, have the same order. Therefore, as shown in Figure 2.35, the effect of optical rotation cannot be ignored. Specifically,

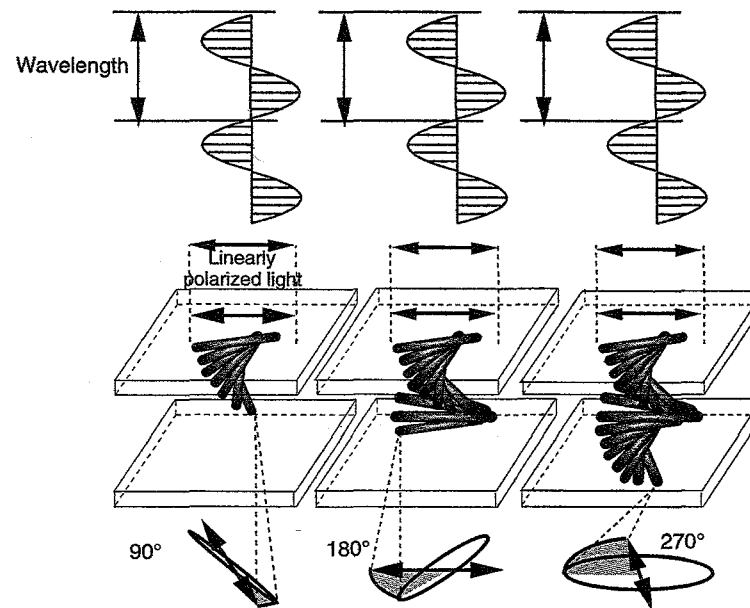
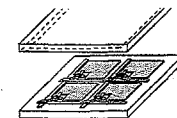


Figure 2.35 Twist-angle dependency of optical rotation

because of its large twist angle, the liquid crystal cannot satisfy Mauguin's condition, thus producing a wavelength dispersion (optical rotation dispersion). The wavelength dispersion causes a coloration.

In the case of an STN liquid crystal, the birefringence term that reflects the wavelength dispersion due to elliptic polarization and the optical rotation term that reflects the twisting must be compensated for in order to solve the problem of coloration. In the D-STN mode, the second LC panel, i.e., the LC panel that has an inverse helix, compensates for both the birefringence term and the twist-induced optical rotation term. In actuality, however, if the term $\Delta n d$ in Equation 2.5 is set to 0, the effect will be the elimination of wavelength dependency. To circumvent this problem, research was conducted in order to compensate only for

the birefringence term, and this led to the development of the F-STN mode. In the F-STN mode, a phase-difference film is used, which has the same retardation as the liquid crystal layer. This film restores the elliptically polarized light to an elliptic polarization which approximates the original linearly polarized light in order to eliminate the wavelength dispersion.

In terms of operation, in the D-STN or F-STN mode the linearly polarized light that has passed through the first polarizer film passes through either the two STN liquid crystal panels or an STN liquid crystal panel and a phase difference film, and reverts to the original linearly polarized light. This prevents the light from passing through the second polarizer film. This state, in which the light is blocked in the absence of a voltage, is the normally black mode. Because the phase-difference film and the polarizer film are similar materials, normally these two films are laminated and are sold as a composite film. Such a film is called an elliptic polarization film (elliptic polarizer).

A drawback of these STN liquid crystal displays, which are based on the use of birefringence, is a poor viewing angle. Figure 2.36 shows a viewing-cone that illustrates problems of viewing angle. A view-cone, which is a commonly used technique for evaluating the viewing angle of a given panel, describes the contrast characteristics of a panel as measured from various directions, and expresses the results in terms of contrast contour lines. The radial direction, which is referred to as the viewing angle, is defined as angle Ψ formed by the angle from which the panel is viewed and the line normal to the panel surface. The center of the viewing-cone is the angle at which viewing angle $\Psi=0^\circ$, which is equivalent to viewing the panel

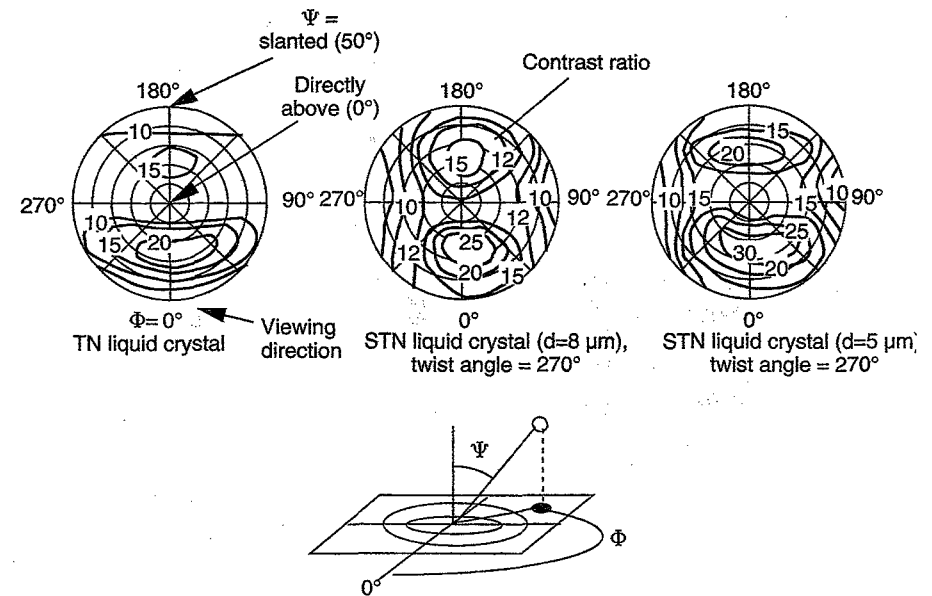
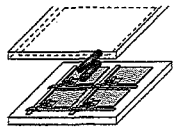


Figure 2.36 View-cones for various LC panels

directly from above. The outermost circumference of the viewing-cone corresponds to the viewing angle $\Psi=50^\circ$. If you use this technique to compare the cell gaps $d=8\text{ }\mu\text{m}$ and $d=5\text{ }\mu\text{m}$, you will see that $d=5\text{ }\mu\text{m}$ affords a larger viewing angle.

It should be noted, however, that although reducing the cell gap improves the viewing angle characteristics, the use of birefringence causes any unevenness in the gap to produce a change in light transmittance and color characteristics. Therefore, this requires that the surface of the substrate be much flatter than in the case of TN liquid crystal panels. Whereas a TN LC panel can tolerate a surface irregularity of $0.1\text{ }\mu\text{m}$, in an STN LC panel this parameter must be controlled to less than $0.05\text{--}0.03\text{ }\mu\text{m}$. Despite the attendant complexity in manufacturing methods and the drawback of a limited viewing angle, the excellent threshold

characteristics of the STN liquid crystal seem to outweigh their disadvantages. Because of its superior display capabilities, STN liquid crystal technology has made considerable gains commercially in vying with passive matrix TN liquid crystal technology.

(3) Compensation (Phase Change) Film

Methods for the manufacture of phase-change films are a logical extension of the polarizer film manufacturing method. As illustrated in Figure 2.37, film made of polycarbonate (PC) or polyvinyl alcohol (PVA) is uniaxially drawn in order to align the molecules in the film and to induce a birefringence anisotropy. The difference from the manufacture of polarizer film is that a considerably different drawing rate is used. Whereas the polarizer film, in which iodine is oriented uniformly, can be drawn using a strong force, a phase-change film is made by carefully regulating the drawing rate in order to ensure that the retardation matches the liquid crystals. Because the film must be made uniformly, the manufacture of phase-change film requires more intricate processes than that of polarizer film.

In recent years, a polymer liquid crystal phase-change film has been developed, in which the optical rotation term, as well as the birefringence term, is compensated. As shown in Figure 2.38, the manufacturing process involves the following operations: First, in order to orient the polymer liquid crystals, a polyimide orientation film is formed. Because the polarizer film cannot withstand the heat of thermal polymerization (250°C), a polymer made by preimidization of the polyimide (polymerizing it beforehand) is dissolved in a solvent, and this solution is applied to the polarizer film. Then, after the orientation layer is oriented

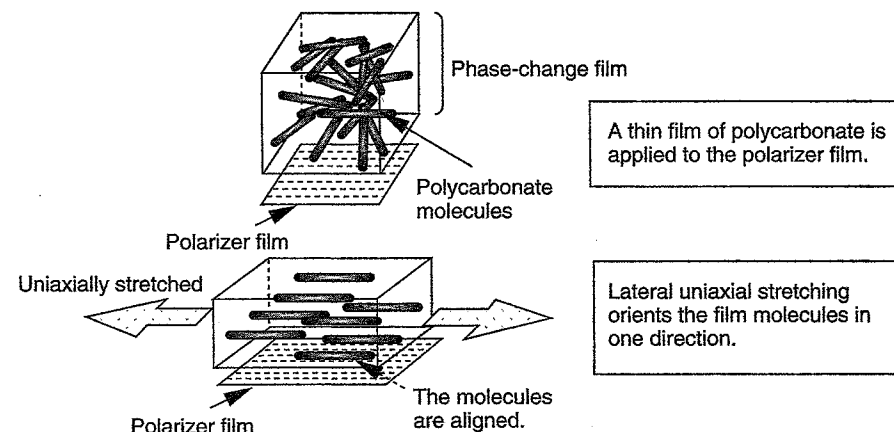
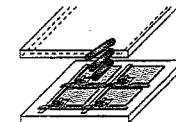


Figure 2.37 Method for the manufacture of a uniaxially stretched phase-change film

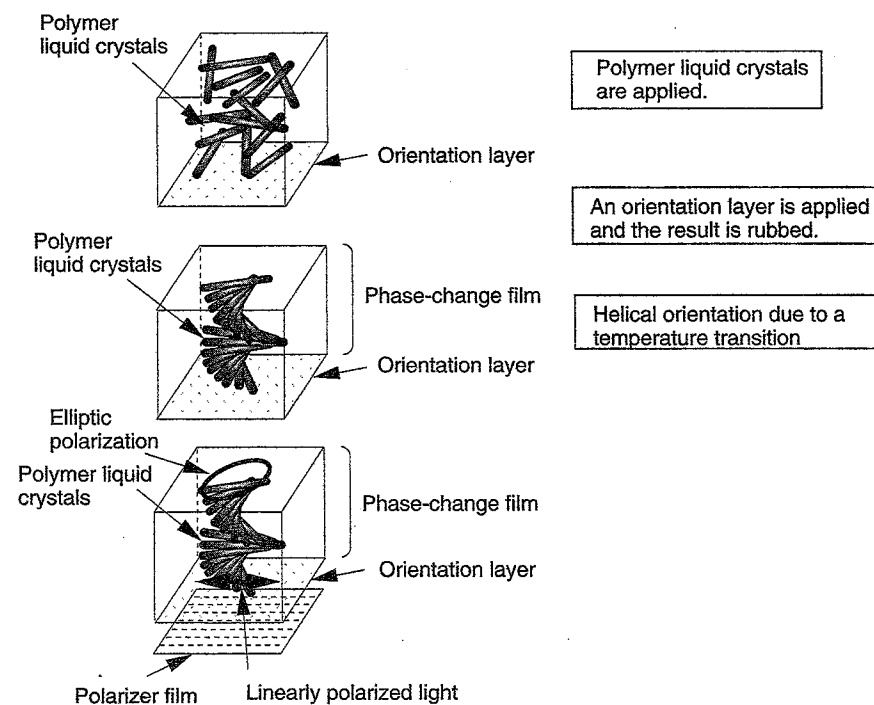
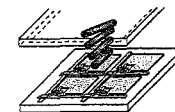


Figure 2.38 Method for the manufacture of a polymer phase-change film



by rubbing, polymer liquid crystals, to which an appropriate amount of chiral molecules are added according to the particular design of a helix structure, are applied to the polyimide orientation layer. The polymer liquid crystals thus oriented provide a compensation for the birefringence term of STN liquid crystals because of the birefringence intrinsic in the liquid crystal molecules. At the same time, the helical structure of the polymer liquid crystals also compensates for the optical rotation term for STN liquid crystals.

In another development, because uniaxially stretched films offer only a limited viewing angle, a special biaxial-stretching (Z-axis) phase-change film has been developed. This film is biaxially drawn through the use of special techniques. As illustrated in Figure 2.39, the method for the manufacture of this film involves the following operations: First, the film molecules are oriented in one direction by means of lateral uniaxial stretching. After this, the film is gently stretched uniaxially in the vertical direction. When this is done, the film shrinks slightly in the lateral direction, thus causing the molecules to become slanted to some extent. The essence of manufacturing know-how lies in achieving a judicious balance between vertical and lateral stretching forces that are applied and the sequence in which the stretching operations are performed. As a final step, the applied stress is released and a protective coating is applied. Because this film alleviates the birefringence in the Z-axis direction, the film offers a wider viewing angle.

2.7.3 Ferroelectric (FLC) Liquid Crystal Mode

The ferroelectric liquid crystal, which is structurally a chiral smectic liquid crystal, forms a helix around a helical axis.

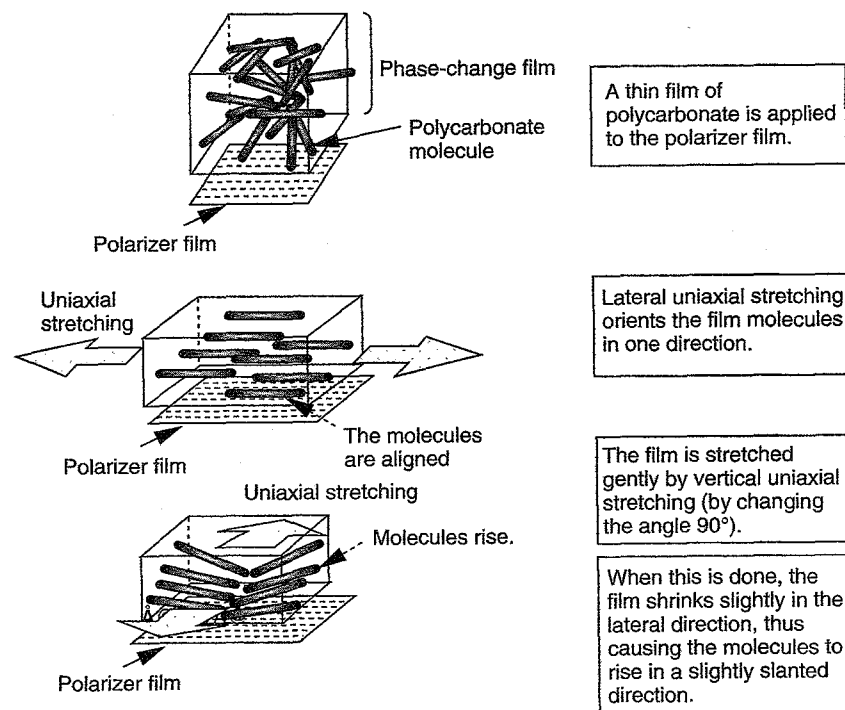


Figure 2.39 Method for the manufacture of a special, biaxially stretched phase-change film

Unlike TN liquid crystals, the helical pitch of a ferroelectric liquid crystal is not very long relative to the wavelength of visible light. As shown in Figure 2.40, it forms a pitch virtually equal to the wavelength of visible light. Under these conditions, a linearly polarized light ray separates into a clockwise, circularly polarized ray and a counterclockwise, circularly polarized ray. The circularly polarized ray with a rotation that coincides with the direction of the helix is reflected and cannot pass through the molecule.

With a reduced cell gap ($d/p < 1.0$), the ferroelectric liquid crystal is devoid of a helical structure, as shown in Figure 2.41. Under these conditions, the liquid crystal

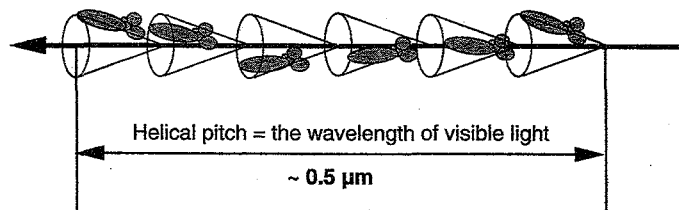


Figure 2.40 Helical pitch of a ferroelectric liquid crystal

assumes two stable states, in a structure called the bistable structure (Figure 2.42). If one of these states is made to coincide with the linear polarization axis of the polarizer film, a display effect can be produced, in which one of the bistable states transmits light and the other does not. Further, unless a voltage is applied, the ferroelectric liquid crystal remains stable in one of its two states, so it can function as a memory. When a voltage is applied, the liquid crystal switches to assume the other state. It is in this manner that FLC display is performed. In order to ensure an adequate bistability, actual FLC panels must have a $2\text{ }\mu\text{m}$ cell gap thickness, and they must achieve a cell gap variation of $0.05\text{ }\mu\text{m}$ or less.

As shown in Figure 2.43, FLC panels have a passive matrix structure. Previously, the liquid crystals in an FLC panel were thought to have a bookshelf structure (Figure

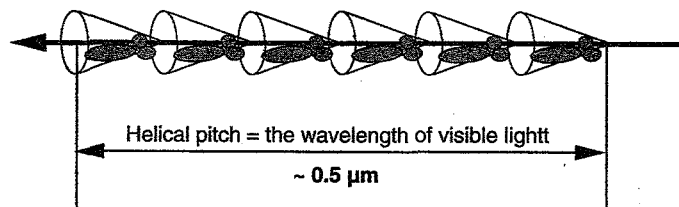
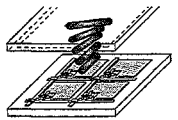


Figure 2.41 Ferroelectric liquid crystal that does not have a helical structure



2.44), in which the smectic layers line up in a bookshelf pattern. However, the structural analyses of defects carried out in recent years have revealed that the liquid crystals are oriented in a chevron structure, in which they form a wedge pattern. Ferroelectric liquid crystals are liable to exhibit unique defects, caused by the rotation of ferroelectric liquid crystal molecules around a cone, and zigzag defects, as well as disclinations and dislocations. Research on what causes zigzag defects revealed that the smectic layers are bent in a wedge pattern, and that zigzag defects

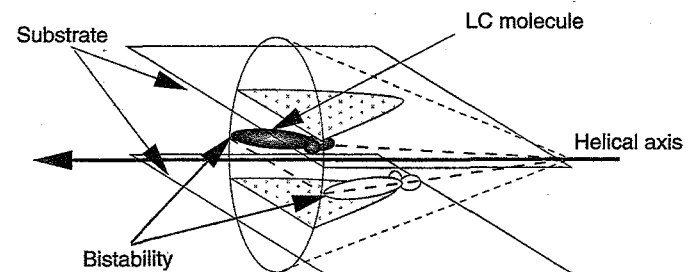


Figure 2.42 Bistable structure of a ferroelectric liquid crystal

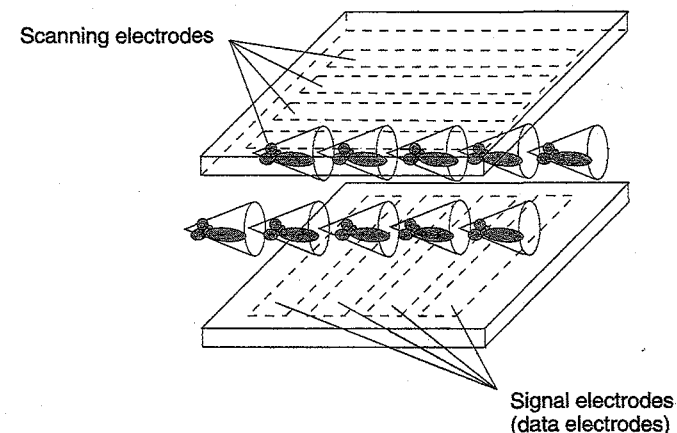


Figure 2.43 FLC panel

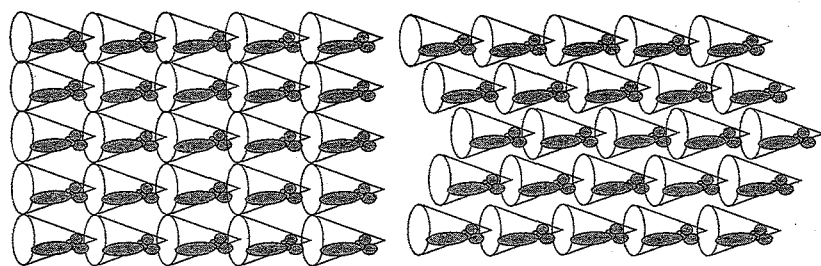


Figure 2.44 Bookshelf structure

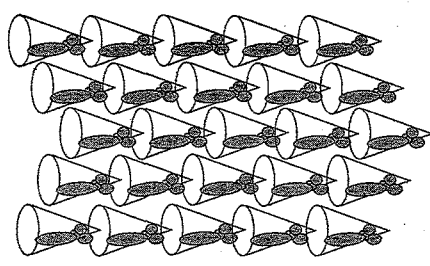
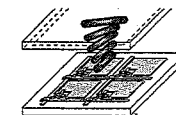


Figure 2.45 Chevron structure

occur at the vertex of each wedge, a discovery which provided proof that ferroelectric liquid crystals have a chevron structure. In addition, ferroelectric liquid crystals are subject to a phenomenon called the Goldstone mode, which is a type of fluctuation that occurs because liquid crystals are a continuous fluid. To control these defects, the manufacture of FLC panels must meet significantly more stringent specifications, including cell gap specifications, than is the case of the production of TN or STN liquid crystals. FLC panels can be produced only when these stringent manufacturing conditions are met.

Let us now assume that ordinary light falls upon an FLC panel from the top, as shown in Figure 2.46. The first polarizer film admits linearly polarized light. The polarizer film is arranged in such a way that the linearly polarized light coincides with the director (the direction of the long axis) of the liquid crystal molecules. This suppresses intramolecular refractive index anisotropy. Consequently, the linearly polarized light that has passed through the first polarizer film passes directly through the liquid crystal molecules. However, because it is at an angle to the second polarizer film, the light is blocked.



Subsequently, when a voltage higher than the threshold value is applied to the LC panel, the ferroelectric liquid crystal molecule shifts into the other stable state, as shown in Figure 2.46. Because the liquid crystal molecule has changed into the other condition of the bistability, the linearly polarized light is now at a certain angle Θ (30° - 50°) to the director (long-axis direction) for the liquid crystal molecule. Therefore, as was explained in reference to Figure 2.18, the birefringence of the liquid crystal molecule divides the light into the directions of the long and short axes. The light propagates through the liquid crystal molecule, and at the outlet it becomes elliptically polarized. The second polarizer film then admits the passage of only specific linearly polarized light from the elliptically polarized light. Further, because this state is produced solely by voltage-switching, after the liquid crystal molecule is inverted, it maintains the inverted state even in the absence of a voltage.

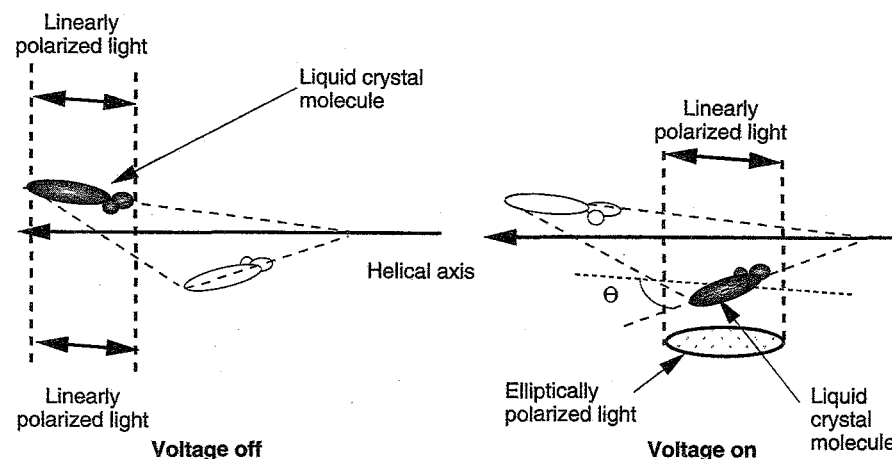


Figure 2.46 How an FLC panel is driven

The short distance in which molecules can undergo an inversion, and the ability to shift their states by rotating a fixed dipole moment around a helical axis, enable ferroelectric liquid crystal molecules to achieve a driving speed that is several orders of magnitude greater than TN or STN liquid crystals. On the negative side, ferroelectric liquid crystals typically have a low contrast of only 20, and they are liable to change from one orientation to another at random. Many of the defects in ferroelectric liquid crystals are caused by a dislocation. The chevron structure can cause defects to occur at the slightest application of a stress.

2.8 LIQUID CRYSTAL DRIVE SCHEMES

After an LC material is selected, the orientation is decided, and the operating mode to be applied is determined, you need to decide how to apply voltage. The dot-matrix method refers to an LC display method in which characters and pictures are displayed as sets of dots. In the following, we describe two drive methods which are typical dot-matrix methods.

2.8.1 Passive Matrix

In the passive matrix drive method, striped electrodes are arranged between two glass plates, so that the electrodes are staggered 90° to one other, as illustrated in Figure 2.47. To apply a voltage at an intersection of the electrodes, you must apply a voltage to each of the mutually crossing electrodes. Any liquid crystal can be used, including nematic, chiral nematic, or ferroelectric liquid crystal (chiral smectic liquid crystal). The passive matrix drive applied to these liquid crystals produces a TN LC panel, an STN LC panel, or an FLC panel, respectively.

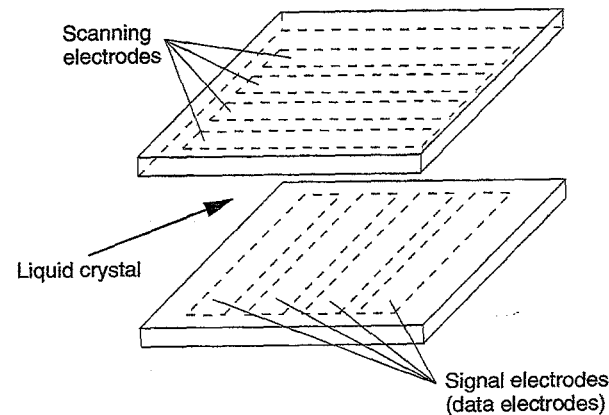
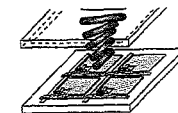


Figure 2.47 Structure of a passive matrix TN liquid crystal panel

In this drive method, scanning electrodes are selected sequentially in pulses. When a scanning electrode is selected, a voltage is applied to the signal electrode that corresponds to a given dot. If N denotes the total number of scanning lines, the duration in which a voltage is applied to a given scanning electrode is $1/N$ of the screen display period, which is referred to as a frame period. In this case, the ratio $1/N$ is called a duty ratio for the pulse drive. Different types of liquid crystals have different duty ratio limits within which the liquid crystal can be driven. The practical duty ratio limit for TN liquid crystal panels is $1/100$. For STN liquid crystal panels, the practical limit is $1/500$, which allows a more detailed display.

2.8.2 Active Matrix

The introduction of the STN and ferroelectric modes, and innovations in drive methods, such as the development of the voltage-averaging method, have solved many of the problems inherent in the passive matrix method. The technique of attaching active elements, such as transistors, to

each of the dots was studied at the same time that the voltage-averaging method was developed. The result is the active matrix method.

As shown in Figure 2.48, the active matrix method involves transmitting a drive voltage to a given liquid crystal element through an active element, which functions as a switch. In a pixel, liquid crystal elements and capacitors are connected in parallel. First, when an active element is turned on, the drive voltage is written onto the pixel. Even when the active element has been turned off, the pixel retains the applied voltage because of its storage capacity. Thus, because of the capacitor, even in the case of a 1/1000 duty ratio signal input time, the pixel retains the

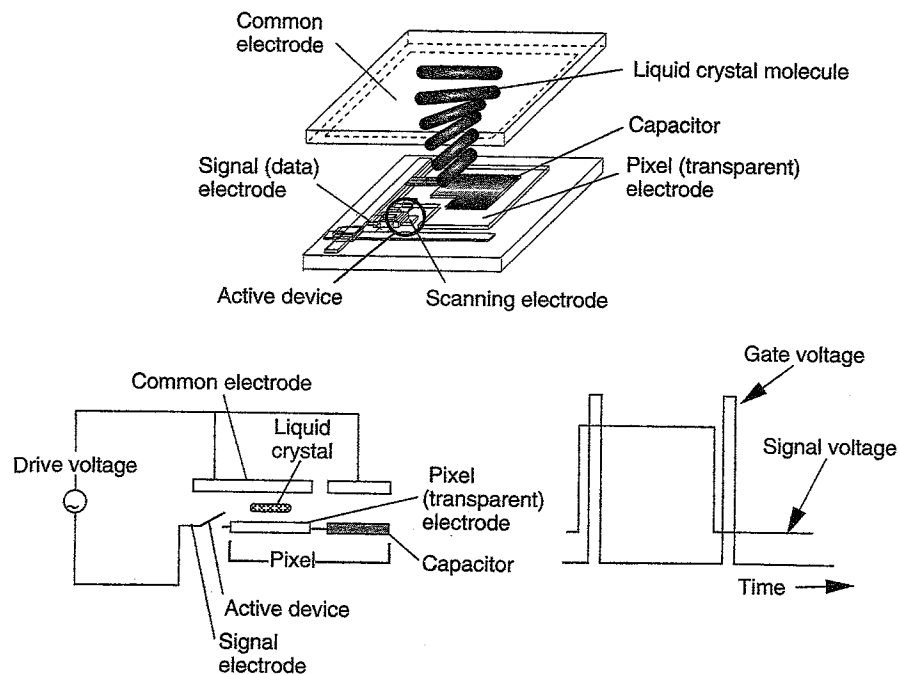
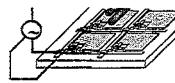


Figure 2.48 Active matrix storage capacity and display time



signal voltage until another signal is imparted. In this manner, the liquid crystal can be driven under the same conditions as the ordinary on/off drive (static drive).

The performance of an active matrix device varies greatly with the type of switching semiconductor device that is incorporated. The following sections describe the MIM device and the TFT device, which is known to offer superior performance.

(1) MIM

Figure 2.49 shows a schematic diagram of a metal-insulator-metal (MIM) drive device. A characteristic of this device is a metal/insulator/metal stacked structure, which confers on the device a bidirectional diode property having a sharp threshold value. In this device, nematic liquid crystals are used as a liquid crystal material, and the TN operating mode is used. Figure 2.50 shows the configuration of an MIM liquid crystal panel. An MIM device is a two-terminal device in which its interconnections, — chromium

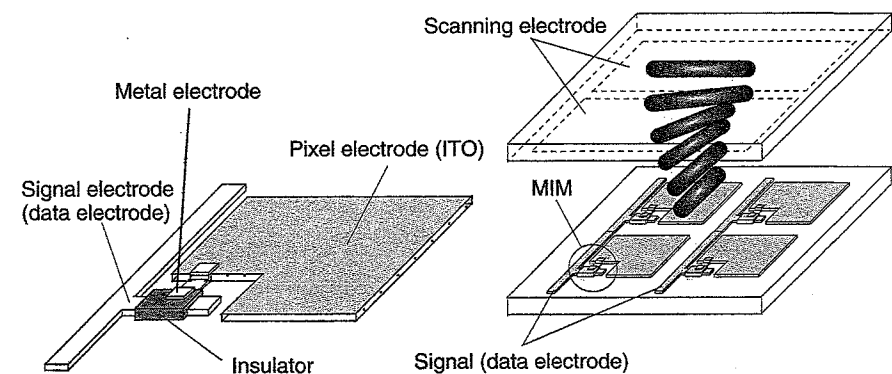


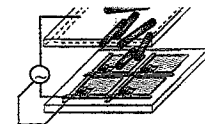
Figure 2.49 A MIM liquid crystal display pixel

Figure 2.50 MIM liquid crystal panel

metal electrode and transparent ITO (indium tin oxide) counterelectrode — are constructed as stripe electrodes, just like passive matrix electrodes. The bus electrode connected to an MIM device functions as a signal (data) electrode, and the transparent ITO counterelectrode serves as a scanning electrode. Although similar to the passive matrix drive method, the MIM drive method does not suffer as much from the problem of crosstalk, which afflicts the passive matrix method, because the MIM's threshold characteristics are governed by the two-terminal device.

A color filter is placed on a substrate that is positioned opposite the MIM device. To drive the liquid crystal in the optimum way, it is necessary to form transparent electrodes on the color filter. However, forming transparent ITO electrodes on the color filter is subject to the influence of the color filter's surface irregularities. Furthermore, because the color filter is made from organic material, controlling surface irregularities during the manufacturing process is a difficult proposition. Although color filters can be made by a low-temperature techniques, the electrodes, which must be low-resistance, require a near-250°C temperature for their formation. The temperature for the formation of the ITO layer and the polymerization temperature of the orientation film are both in the vicinity of 250°C. This is the critical limiting factor on the thermal properties of the color filter. This issue has been solved through advances in materials and manufacturing processes (flatness), and as a result, the MIM drive method has gained wide acceptance.

On the other hand, from the standpoint of increasing the production yields for the electrode patterning process, the method of forming ITO electrodes on a glass substrate



and then forming a color filter, rather than forming ITO electrodes on a color filter, is advantageous. However, because this method involves sandwiching a color filter layer between electrodes, the problem of a high drive voltage arises as a trade-off. To solve this problem, it is necessary to achieve a greater uniformity of film thickness and a further reduction in the electrical resistance of the color filter. The latter approach is used in some of the MIM color filters that are made by dyeing.

(2) TFT

Figure 2.51 shows a schematic diagram of liquid crystal pixels in which TFT active devices are used. Figure 2.52 shows a schematic diagram of a TFT liquid crystal panel. In the term "TFT device," "TFT" stands for "thin-film transistor," meaning that the device is a transistor constructed from thin-films.

The TFT is a three-terminal switch, which is made by constructing gate, source, and drain electrodes in a thin-film semiconductor. When an "on" voltage is applied to a

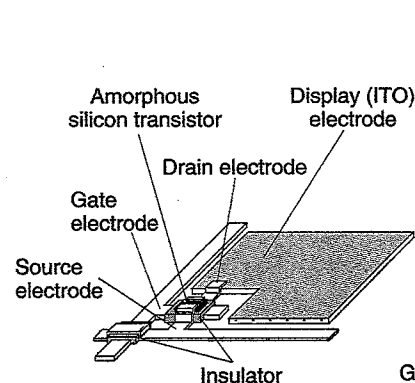


Figure 2.51 TFT liquid crystal display panel

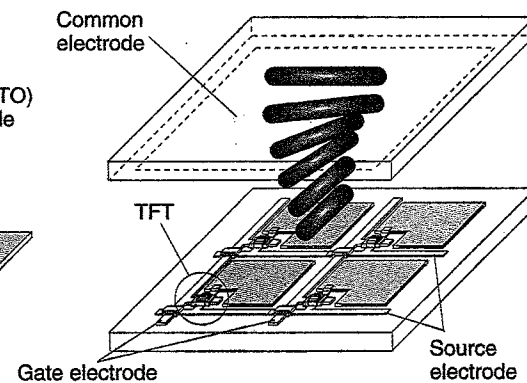
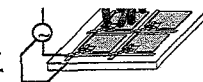


Figure 2.52 TFT liquid crystal panel

gate electrode, current flows from the source (signal) electrode to the drain electrode, or vice versa, as the case may be, and current passes through the body of the semiconductor. When an "off" voltage is applied to a gate electrode, the passage of current between the source and drain electrodes is blocked. Thus, the gate electrode functions as a gate for electrons, turning the TFT switch on and off. When the TFT is turned on, a voltage is applied from the drain electrode to the pixel electrode (ITO transparent electrode), so that a drive voltage is applied to the liquid crystal devices between the pixel that has been turned on and the opposite common electrode (the transparent ITO electrode that covers the entire surface of the opposite substrate). Similarly, a voltage is applied to capacitors that are connected in parallel with the liquid crystal devices. When an "off" voltage is applied to the gate electrode, the TFT turns off, and, because of the voltage stored in the liquid crystal pixel electrode and the capacitor, the liquid crystal pixel retains its voltage.

For TFT displays, nematic liquid crystals are used as a liquid crystal material, and the TN operating mode is used. A characteristic of the TFT liquid crystal is that the voltage (drive voltage) that is actually applied to the liquid crystal can be varied by regulating the voltage applied to the source electrode. Stated simply, the gate electrode controls whether a voltage is applied to the liquid crystal, and the source electrode determines the magnitude of that voltage. Consequently, because the liquid crystal drive state can be controlled by a source electrode, any intermediate-value transmittance for the liquid crystal device can be set arbitrarily. This makes it possible to implement a gray-scale display, in which the light level between black and white



can be expressed in several gradations. The TFT liquid crystal device, as would be expected, does not suffer from the problem of crosstalk, which afflicts the passive matrix scheme. Furthermore, because the ITO counterelectrodes on the color filter array do not require patterning, the TFT method can significantly reduce the manufacturing cost of the color filter component.

As an additional feature, a storage capacitor enables the TFT device to retain a signal voltage until another signal is imparted, even if the signal input time is short. The result is an improved contrast ratio.

In the case of the normally black mode, the two polarizer films are arranged in parallel (parallel Nicols), as shown in Figure 2.53. Therefore, when the liquid crystal is twist-oriented, i.e., if a voltage is not applied, the light ray that has passed through the first polarizer film and that has become a linearly polarized light twists 90° as it propagates through the liquid crystal and along the helical structure. Therefore, this light is prevented from passing through the second polarizer film, which is parallel to the

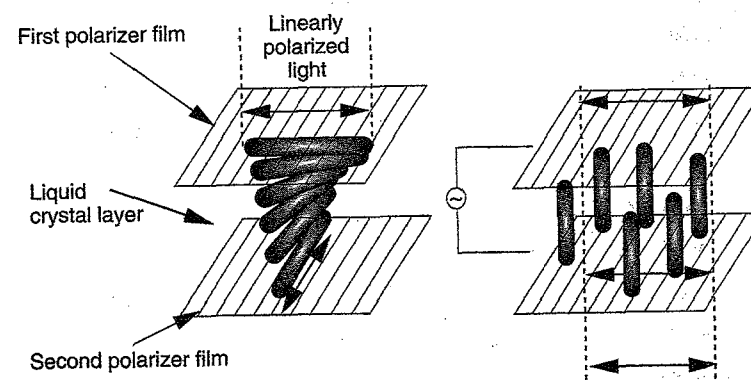


Figure 2.53 Normally black mode

first polarizer film. If no light can pass, the result is a completely black (normally off) display. However, the phenomenon of the wavelength dependency of the birefringence due to optical rotation, which is pronounced in the STN liquid crystal, also manifests itself to some extent in the TN liquid crystal. In the case of the normally black mode, the light transmittance I can be expressed in Equation 2.6 (Gooch-Tarry equation), as illustrated in Figure 2.54, where the twist angle is denoted as Θ

$$I = \left[\sin^2 \left(\Theta \sqrt{1 + u^2} \right) \right] / (1 + u^2) \quad (2.6)$$

$$\text{where, } u = \frac{\Delta n d}{\lambda} \cdot \frac{\pi}{\Theta}$$

In Equation 2.6, when u^2 is 3, 15, 35, 63, ..., then the transmittance I is 0. Under this condition, the incoming linearly polarized light twists exactly 90° , and exits as a linearly polarized light that does not contain any elliptically polarized light. The curve at which u^2 is 3 is called the first minimum, and the curve at which u^2 is 15 is called the second minimum. For each wavelength λ , there is a different retardation value $\Delta n d$ at which the transmittance becomes a minimum. For example, if $\Delta n d$ is set as the first minimum for red (R in the figure), at other wavelengths there is a slight leakage of light, as shown in Figure 2.54. This is the most significant drawback of the normally black mode. To increase the contrast, an important requirement is to darken the black state, rather than to increase the white luminous energy or the color temperature to the white state. Thus, it is important to minimize the amount of light leakage and to avoid coloration due to variation in the black level hue.

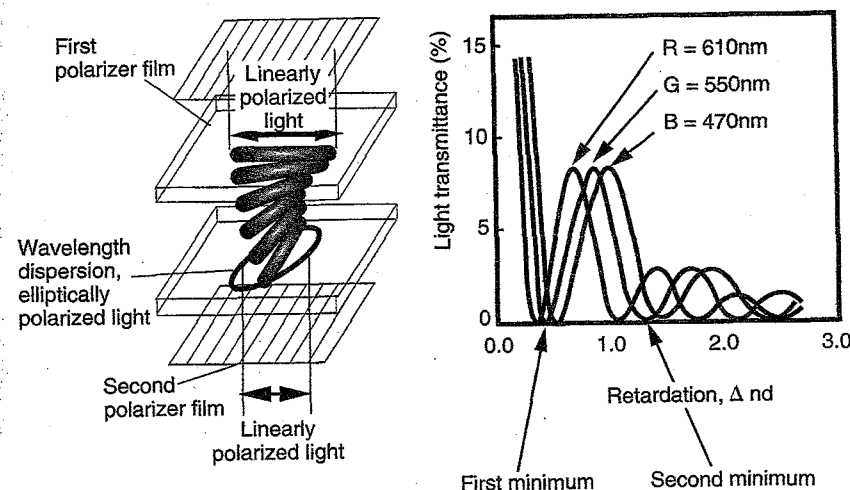
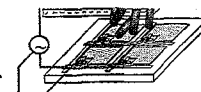


Figure 2.54 Wavelength (optical rotation) dispersion of TN liquid crystals

Two approaches are being investigated to solve this problem: a multi-gap method to control the optical rotation, and a drive method based on the normally white mode.

The multi-gap method is based on the idea that, if a wavelength-dependent optical rotation occurs at various wavelengths, as shown in Figure 2.55, the percentage of optical rotation should be made equal for each wavelength. In other words, this method involves setting the ratio d/λ , which is the proportion of light of a given wavelength passing through the liquid crystal, equal to a multiple of the wavelength. Specifically, if $u^2 = 15$ in Equation 2.6, the thickness of the color filter on the substrate is varied so that the cell gap for a wavelength will be $9 \mu\text{m}$ for red (R), $8 \mu\text{m}$ for green (G), and $7 \mu\text{m}$ for blue (B) (equivalent to approximately 15 times a given wavelength). The result is that the retardation factor in Equation 2.6 is

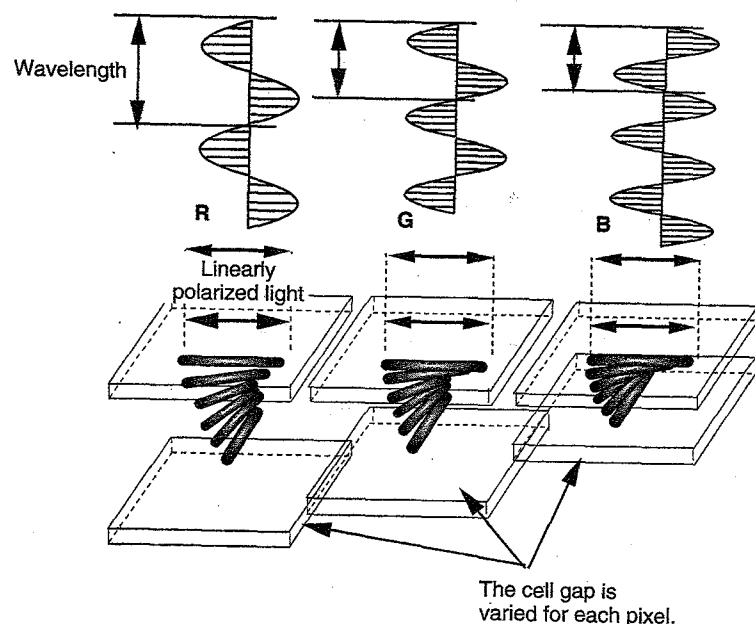


Figure 2.55 Multi-gap method

constant. Although the twist angle Θ can be set to 90° for all pixels, due to the effect of the orientation film that is applied to both top and bottom substrates, in actuality, attempts to control the cell gap for the exceedingly small pixels are stymied by the problem of product variability during mass production. Therefore, controlling the cell gap directly is not feasible from a mass production standpoint.

The problem was finally solved by adopting the normally white mode shown in Figure 2.56. In the normally white mode, the two polarizer films are arranged at right angles to each other (crossed Nicols). In the presence of a voltage, the liquid crystal molecules rise up perpendicularly. The linearly polarized light that has passed through the first polarizer film proceeds directly to the second polarizer film, where it is blocked. In this case, since the liquid

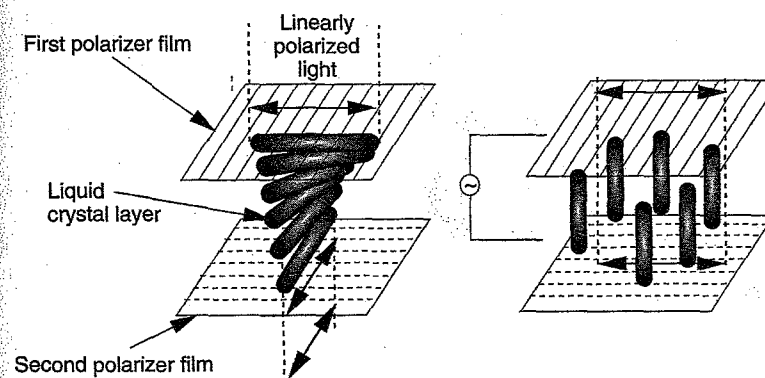


Figure 2.56 Normally white mode

crystal exhibits neither a birefringence nor an optical rotation, there is no wavelength dependency. Therefore, the result is pure black, the color of the polarizer film. It is in this manner that true black, free from any wavelength dependency, is obtained. Therefore, the normally white mode has now gained wide acceptance.

2.9 CHARACTER DISPLAYS

There are two ways to produce a display on a liquid crystal: the segment method, in which the characters and pictures to be output are displayed in terms of patterned electrodes (Figure 2.57) and the dot-matrix method, in which characters are displayed in sets of dots (Figure 2.58). In the case of the dot-matrix method, the greater the number of character dots, the clearer the resulting display. Each dot is called a pixel, and the set of pixels that forms a character is referred to as a character font. As concrete examples, the segment drive method is used for simple displays, such as those in calculators, while the dot-matrix method is used for high-quality displays, such as in personal computers.

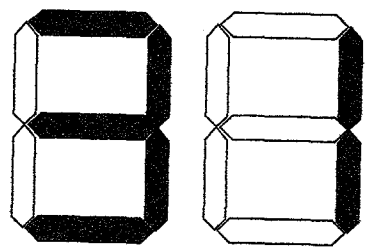


Figure 2.57 Example of a segment-method display

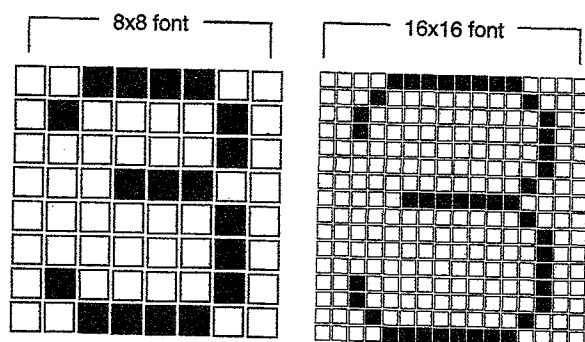


Figure 2.58 Example of a dot-matrix display

Two drive methods are employed. One method, called the static drive method, involves turning each pixel on and off by applying a voltage to it. The other method, called the multiplex (dynamic) drive method, involves driving several pixels at a time by time-division in a pulse drive.

The static drive method requires that each pixel be wired. Although this method entails complicated wiring, because each electrode operates independently, pixels are immune to the effects of adjacent electrodes. This makes for a simple drive method.

However, as the screen display density is increased by making fonts increasingly finer from 16x16 dots to 32x32



dots to 64x64 dots, and so forth, the problem of wiring rapidly becomes more complex. In the case of a VGA color LC panel, for example, the display density is 1920 (640 x RGB) x 480 dots. Driving this panel by the static method would require the number of drive electrodes equal to this number (921,600) plus the number of common electrodes (normally one electrode). Thus, it is not feasible to achieve the required extent of wiring using the static drive method. Therefore, the VGA display requires the use of the multiplex drive method. The multiplex method requires a number of signal electrodes equal only to the sum of vertical and horizontal electrodes, as illustrated in Figure 2.59. Thus, in the case of a color LC panel, only 1920 (640 x RGB) + 480 electrodes (2,400) are required. Since only one connection is required per row of electrodes, only one electrical connection needs to be made between pixels. This level of wiring can be achieved on a mass-production basis. In the case of passive matrix drive, a voltage can be applied at an intersection of these electrodes simply by selecting the crossing signal and scanning electrodes.

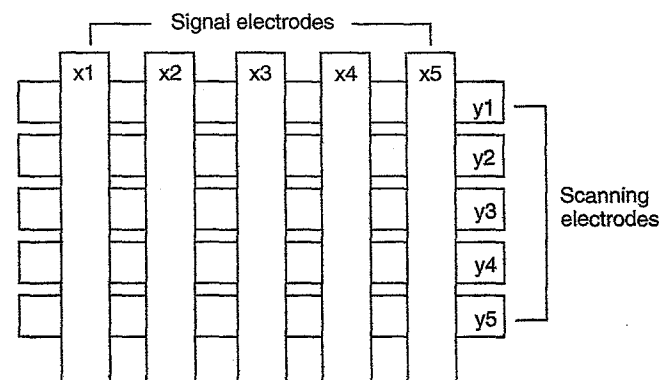


Figure 2.59 Dot-matrix multiplex drive

2.10 CROSSTALK

In the passive matrix drive method, the scanning electrodes are selected sequentially for a specified length of time, and when a given scanning electrode is selected, the signal electrode that corresponds to a given dot and is connected to the scanning electrode is selected, and a voltage is applied to that signal electrode. A careful examination of the circuits, however, indicates that a voltage is not exclusively applied at a selected crossing point. For example, there are current paths that bypass the intended given connection which wind up driving other display pixels. This phenomenon is called crosstalk. Figure 2.60 shows the equivalent circuit for an LC panel. The part of the liquid crystal layer that is driven is indicated as a capacitor. Because liquid crystals are insulators, they are driven in the same way as a capacitor is charged and discharged. In Figure 2.60, the scanning and signal lines indicated by the

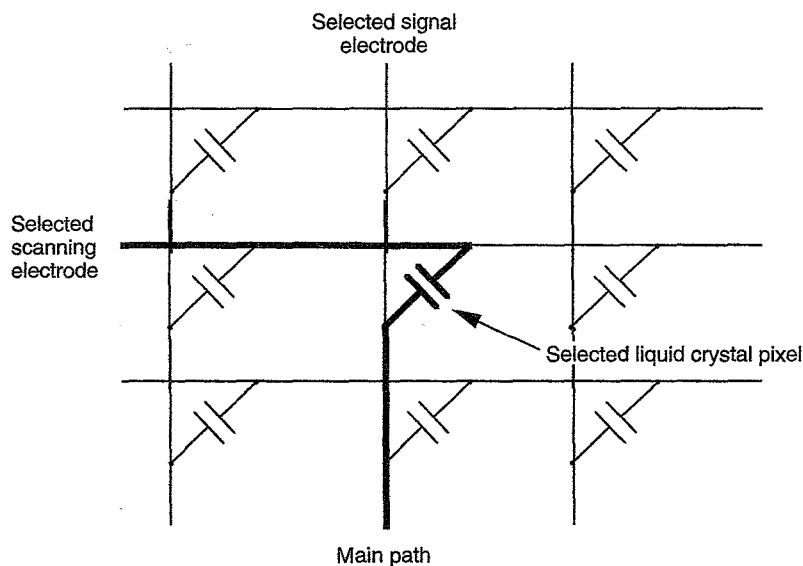
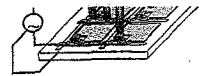


Figure 2.60 Equivalent circuit for an LC panel



bold line are selected. The intersection of these lines is turned on. The route that leads from the selected signal line to the intersection that is turned on is called the main path. A close look at the circuit reveals that there is another, secondary path in addition to the main path, as shown in Figure 2.61. The phenomenon in which non-selected pixels are driven due to a secondary path is called crosstalk.

Because the phenomenon of crosstalk produces blurred images, ways to solve this problem by means of a suitable drive method have been investigated. This has led to the development of the voltage-averaging method. In the case of the circuit (3x3) illustrated in Figure 2.62, if a voltage V_0 is applied to a selected scanning electrode, a voltage is applied to the remaining two non-selected scanning electrodes. If the ground potential (0 V) is applied to a selected signal electrode, a voltage is applied to the remaining two

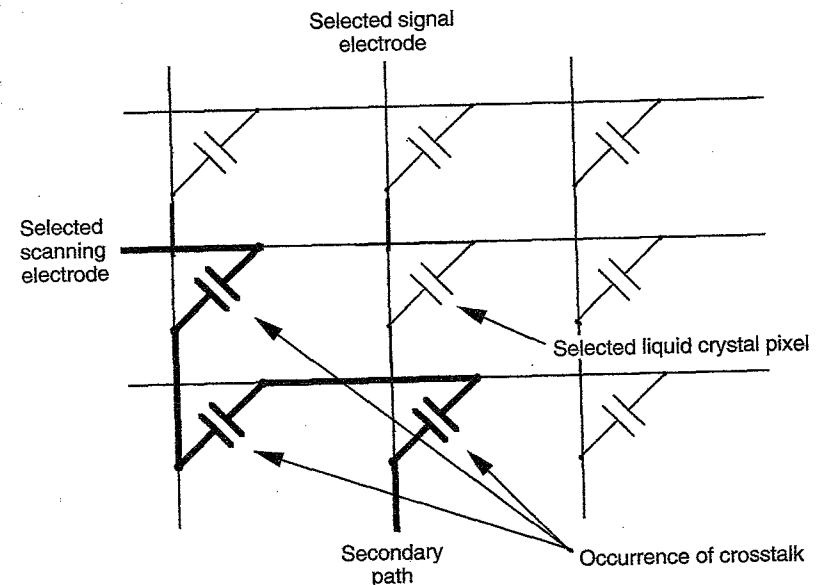


Figure 2.61 Crosstalk due to a secondary path

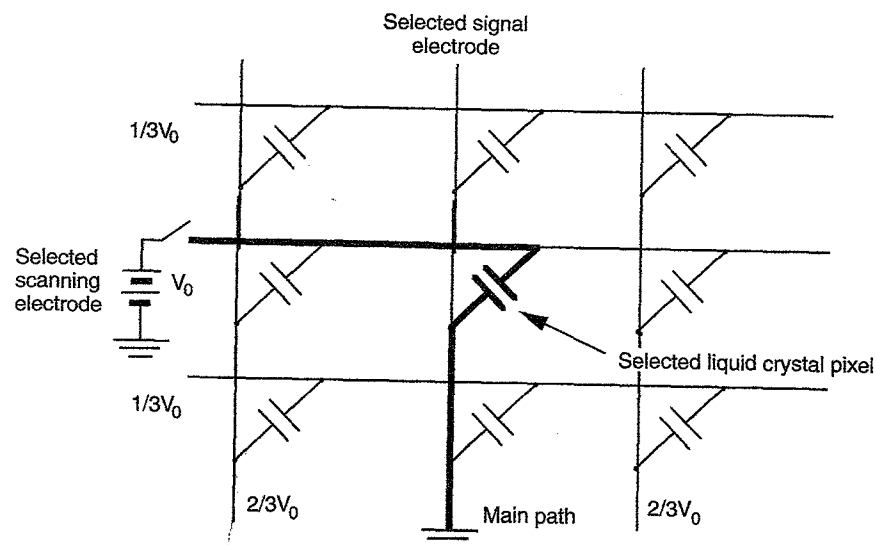


Figure 2.62 Voltage-averaging method

non-selected signal electrodes. Therefore, each of the non-selected pixels only receives a potential difference (voltage) of $1/3 V_0$. This method, which involves applying a uniform crosstalk voltage to each of the pixels, is called the voltage-averaging method. In this case, the level of the "on" voltage is V_0 , and that of the "off" voltage $1/3 V_0$. Further, in a panel containing N scanning electrodes, crosstalk can be suppressed by applying the voltage indicated in Equation 2.7 to each of the non-selected scanning electrodes.

$$\frac{1}{\sqrt{N+1}} V_0 \quad (2.7)$$

The active matrix method, on the other hand, seeks to solve the problem of crosstalk by means of a circuit design rather than by means of a drive method. To illustrate this approach in an easy-to-understand manner, Figure 2.63

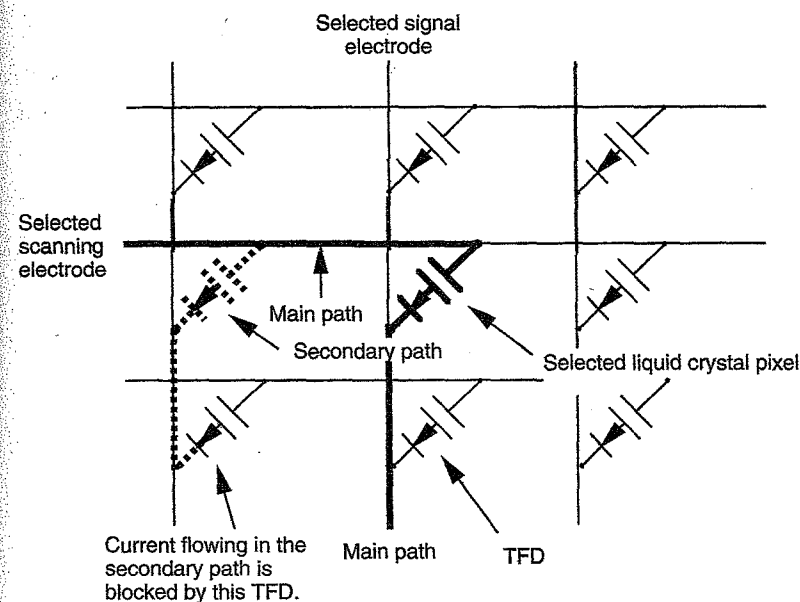


Figure 2.63 Equivalent circuit for a TFD liquid crystal panel

depicts an example using a thin-film diode (TFD). As depicted in the figure, the provision of rectifier devices on a secondary path prevents any current from flowing in that secondary path. Thus, the active matrix method can greatly reduce the problem of crosstalk.

2.11 IMAGES IN MOTION

Character and graphic images that do not move are called still images. By contrast, images that move are called animated images. If the still image of a picture is changed in a short interval of time, the image-retention capacity of the eye produces the illusion that the picture is moving. This is the underlying principle behind motion pictures. To illustrate this phenomenon, still pictures are printed at the upper right-hand corners of the pages of this book. If you flip the pages rapidly, you will see a motion picture. Thus,

animated pictures can be produced by sequentially changing a given still picture in a time series. The length of time that a human is unable to distinguish the retained image of a picture from another picture is approximately 1/30 second. A screen becomes a motion-picture screen by changing the screen image at a rate exceeding this time interval. TV images can be displayed by driving a dot-matrix LCD at this speed.

2.12 DISPLAYING COLORS

In a color TFT display, color filters comprising the three primary colors (red, green, and blue (R, G, B)) are provided on the common electrode substrate of the TFT LC display so that the color filter elements are in one-to-one correspondence with the pixels on the TFT array side. Using a suitable balance between RGB, colors can be produced by additive mixing. To accomplish this, first the intensity and color of light must be defined quantitatively, and the resulting value must be adjusted to match the characteristics of human visual perception. In this manner, the desired color can be reproduced on a color TFT display. Following is a description of how the design process is accomplished.

2.13 LIGHT INTENSITY VS. WAVELENGTH

The light that we see around us, such as sunlight, room lights, and the light reflected from objects, is composed of light rays of various wavelengths rather than being light of a single wavelength. Further, the light rays of different wavelengths normally have different energies. To express these properties, the light rays are classified by the

wavelength, and the amount of energy associated with each wavelength is indicated. This type of classification is called an energy spectral distribution. The wavelength of sunlight varies continuously. When examined in detail, sunlight consists of indefinitely subdivisible wavelengths, such as 600 nm, 600.3 nm, 600.35 nm, and so forth. Therefore, sunlight cannot be classified in terms of discrete wavelengths. For convenience, the wavelength spectrum of sunlight is divided into bands, and the amount of energy contained in each band is expressed. Monochrome light consists of a narrow band of light rays.

For example, let us consider a 5 nm band, as shown in Figure 2.64. To measure the energy of a light ray with a 600 nm wavelength, the light ray with a bandwidth of 597.5 nm to 602.5 nm is treated as a ray of 600 nm wavelength. Assume that the total energy of light contained in this 5 nm band is S watts. Note that it would not be appropriate

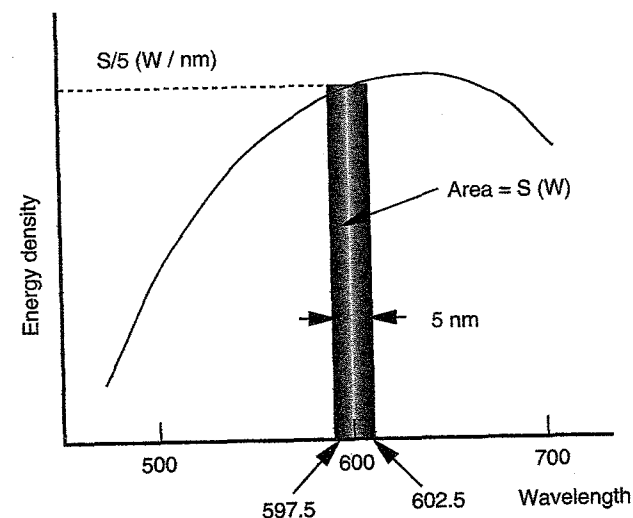


Figure 2.64 Spectral density of energy

to regard the light ray with a 600 nm wavelength as having an energy of S watts, since the 600 nm band also contains the energy of light components having other wavelengths. Therefore, the value $S/5$ (W/nm), which is S watts divided by 5 nm, is taken as the amount of energy contained in a light ray of 600 nm wavelength. This is called the spectral density of energy.

For characterizing a display's light source color, in almost all cases it suffices to determine a relative, rather than an absolute, spectral density value. Therefore, the actual spectral density of energy is expressed by plotting relative energy spectral densities, such as specific energy, relative energy, or relative emission intensity, on the ordinate of the type of spectral distribution shown in Figure 2.65. Using Figure 2.65, it is possible to express the intensity of light for each wavelength.

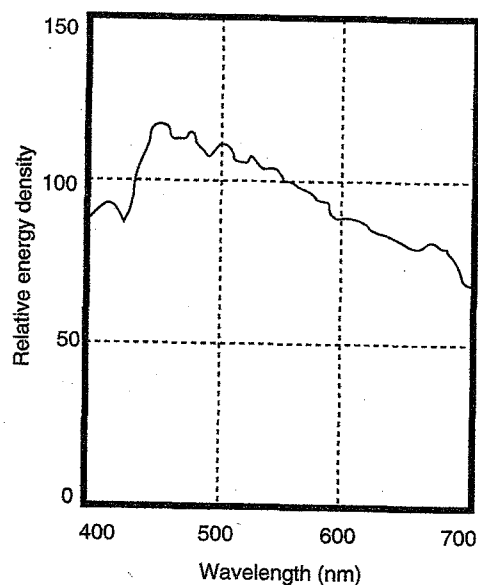


Figure 2.65 Spectral distribution of daytime light

2.14 THE SENSATION OF LIGHT

As mentioned previously, light consists of various wavelengths. The human eye, however, does not see all wavelengths. The light that can be seen by eyes, or visible light, is limited to the wavelength range of 380 nm to 780 nm. Further, as shown in Figure 2.66, the eye senses different colors as a function of wavelength. Also, the eye senses different brightness values as a function of wavelength. Therefore, the type of spectral distribution shown in Figure 2.67 does not necessarily translate into a brightness distribution as sensed by the eye.

The eye senses brightness differently at each wavelength of light. It should be noted that color and brightness are entirely different entities. For example, in a comparison

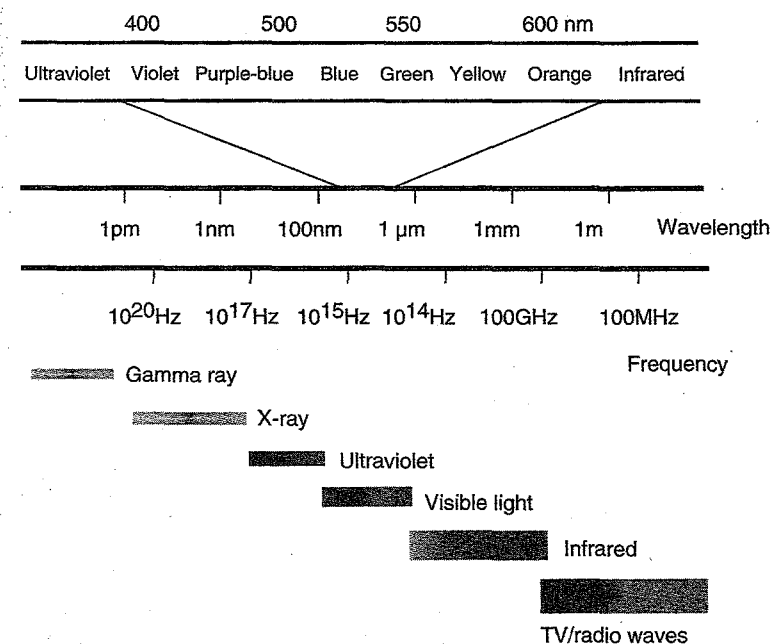


Figure 2.66 Classification of electromagnetic waves and wavelengths

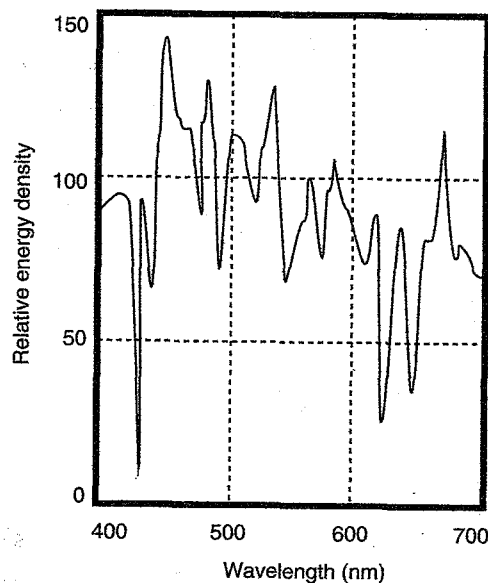


Figure 2.67 Spectral distribution of light sources

of yellow light and blue light, some people might say that the yellow light appears brighter. However, by adjusting the light intensity, that is, the energy of light, it is possible to make two light rays equal in brightness, or to make the blue light ray appear brighter than the yellow light ray. Thus, brightness and color are mutually independent properties.

Let us now examine the extent to which one can sense the brightness for each wavelength. To do so, we view monochrome light rays of different wavelengths and compare the amounts of energy at which the monochrome light rays appear equal in brightness. Because different people may sense brightness differently, we take the average of the readings obtained by many people. However, it has been confirmed that there is little individual difference in color sensation.

The brightness sensation thus evaluated is called spectral luminosity efficacy. These measurements are taken in the visible light region, and the ratings are expressed in relative values, with the spectral luminosity efficacy of the wavelength that requires the least amount of energy to achieve the same luminosity sensation being set to 1. This value is called luminous efficiency. As shown in Figure 2.68, the human eye is most sensitive to light rays of 555 nm wavelength.

The energy of a light ray is expressed in units of watts (W). The luminosity of light as sensed by the eye is indicated by the quantity luminous flux, which is measured in lumen (lm). For each wavelength, the relationship between energy (emission flux) and brightness (luminous flux) can be defined in terms of luminous efficiency. Therefore, if we can determine how many lumens correspond to one watt, we can derive the luminous flux of a light ray from the energy value of that light ray. Monochrome light of 555 nm

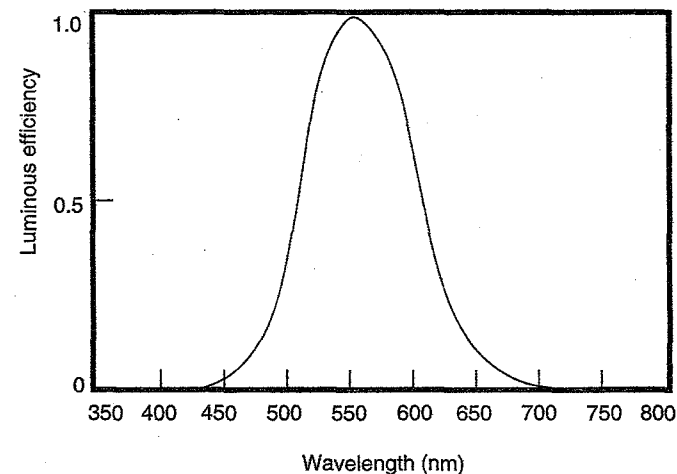


Figure 2.68 Luminous efficiency of CIE standard light (brightly lit location)

wavelength having an energy of one watt is defined as a 683-lumen luminous flux. This is expressed in Equation 2.8:

$$\text{Luminous flux (lm) of monochrome light} = 683 \text{ (lm/W)} \times \text{luminous efficiency} \times \text{energy of the monochrome light (W)} \quad (2.8)$$

In addition to luminous flux (lm), luminosity can be expressed in terms of luminous intensity (cd), luminance (cd/m²), and illuminance (lx). The fundamental measure of brightness is luminous flux. Interested readers may wish to consult reference books for definitions of the other measures.

2.15 THE SENSATION OF COLOR

In contrast to the sensation of luminosity, how does the sensation of color work? As shown in Figure 2.69, there are three basic properties of color: hue, saturation, and brightness.

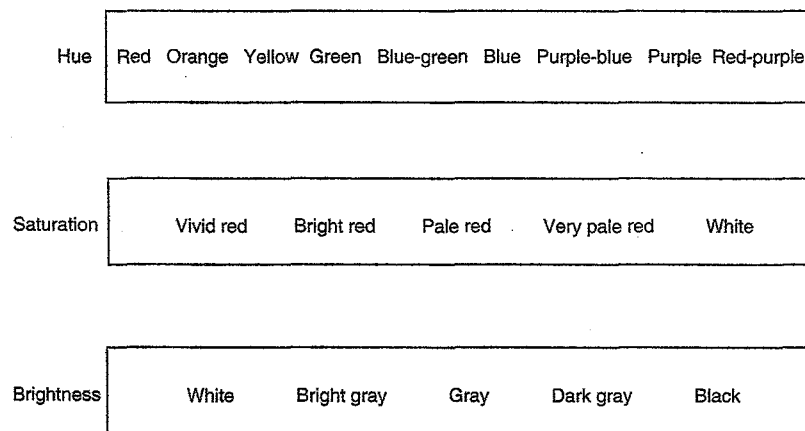


Figure 2.69 Three attributes of color

(1) Hue

Colors such as red, orange, yellow, green, blue, purple-blue, purple, and red-purple are called hues. This is the first property of color.

(2) Saturation

Light coming directly from a source, such as sunlight or fluorescent light, that has not been split into component light rays by a prism, imparts a light or dark sensation, as well as luminosity. Sunlight appears white during day, dim and gray at dusk, and totally dark when the sun has set. White, gray, and black are not components of hue. Because these are attributes of light that appear before the light ray is decomposed into its spectral components, they are not part of color as hue. Such colors are referred to as achromatic colors.

Color can be classified in terms of vividness, ranging from achromatic colors, lightly colored pale colors, and vivid colors that can be decomposed by a prism. Such vividness, or saturation, is the second property of color. If a light ray is colored, no matter how slightly, it is called a chromatic color, as opposed to an achromatic color.

(3) Brightness

The third property is brightness, which refers to the luminosity of color. A given color can be either bright or dark. Luminosity was discussed previously. An achromatic color is one in which the only color attribute present is brightness.

As illustrated in Figure 2.70, the three properties of color can be expressed mathematically and digitally by constructing a diagram in which the center axis describes brightness, from white to black; in which the circle plots

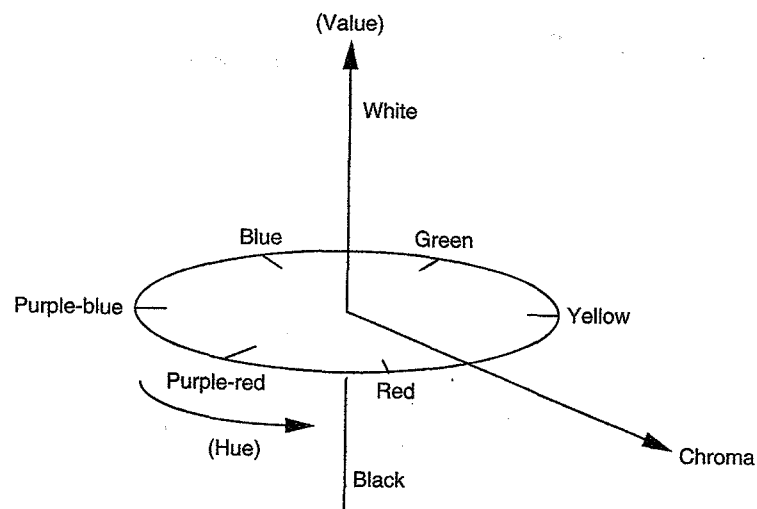


Figure 2.70 Relationship between the three attributes of color hue, beginning with red, changing to green, blue, and red-purple, and returning to red; and in which a radial diagram, radiating from the center, represents saturation, or chroma.

2.16 MATHEMATICAL REPRESENTATION OF COLOR

The quantity of RGB must be expressed in units of measure in terms of color intensity or impact, so that two RGB colors of the same intensity have the same quantity. How should we define the intensity of a color? If all the RGB colors have the same intensity, the three colors are well-balanced; they produce white without a tinge of red, green, or blue. Therefore, the unit of measure should be defined so that if the quantities of red, green, and blue are equal, mixing these colors produces white.

Units of measure of the intensity of a color include luminous flux and luminance, both of which measure brightness. If the luminance of the red, green, and blue

colors to be mixed is changed, the resulting color also changes. Although on the surface luminance may appear an appropriate measure of the quantity of RGB, even if the quantity (energy) of RGB, as discussed above, is equalized, the intensities of the constituent colors are not equal. Therefore, luminance is not an appropriate measure. In fact, mixing the RGB colors of the same luminance does not produce the color white.

Since the energy of light perceived by the eye is brightness, attempts have been made to determine the unit of measure of RGB based on a brightness scale as perceived by the eye. The respective brightness levels of red, green, and blue produce white when the colors are mixed. Their combined brightness is used as a unit of measure of each color. Once this is accomplished, energy and brightness can be interchanged by means of a luminous efficiency scale.

The first task in measurement is to determine the three primary colors, RGB. The difficulty lies in the fact, for example, that there are many shades of red. Since different shades of red require different RGB mixing amounts, the same red color should be used all the time. The same is true of green and blue. Consequently, the CIE (Commission Internationale de l'Eclairage — the International Committee on Illumination) uses the monochrome light rays of R (700.0 nm), G (546.1 nm), and B (435.8 nm). As a next step, a reference white color is prepared, as shown in Figure 2.71, and the brightness of RGB is adjusted so that the resulting mixture produces a white color that is equal to the reference white color. For a reference white color, white light rays of fixed energy are used. These are components of white light that have an equal spectral energy

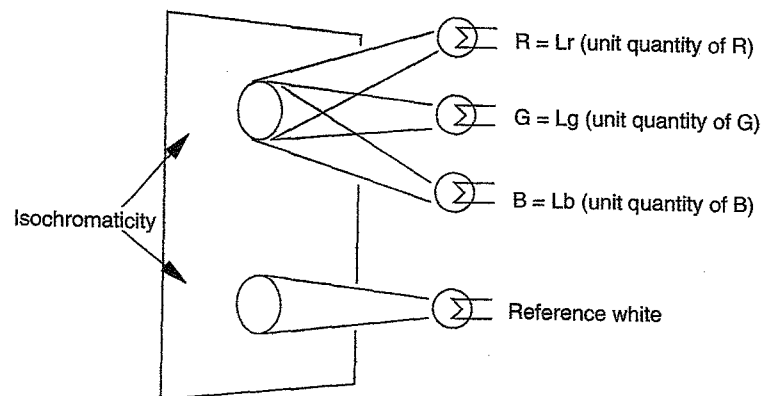


Figure 2.71 Experiment on the isochromaticity of white

density in the visible wavelength region. When the reference white is the same color as a mixture of RGB, the brightness values (luminous fluxes) of RGB are defined as L_r , L_g , and L_b (lm), respectively, each with a quantity of 1 unit. Thus, one unit of the quantity of R is defined as L_r , one unit of the quantity of G defined as L_g , and one unit of the quantity of B defined as L_b . In this way, the original objective can be achieved so that when R, G, and B are mixed in equal amounts, a white color results. The required ratio between L_r , L_g , and L_b to produce white can be defined as in Equation 2.9:

$$L_r : L_g : L_b = 1.0000 : 4.5907 : 0.0610 \quad (2.9)$$

In the next step, RGB are mixed in the brightness units defined as Φ_r , Φ_g , and Φ_b (lm) in order to produce other colors. Since the quantity of the three primary colors is measured in units of brightness/unit brightness, as defined in Equation 2.10,

$$\begin{aligned} \text{(Quantity of the three primary colors)} = \\ \text{(brightness) / (unit brightness)} \end{aligned} \quad (2.10)$$

in this case the quantities of R, G, B can be defined as in Equation 2.11:

$$\begin{aligned} (R) = \Phi_r / L_r, (G) = \\ \Phi_g / L_g, (B) = \Phi_b / L_b \end{aligned} \quad (2.11)$$

The set of these RGB quantities is referred to as tristimulus values. These rules are generalized by the organization CIE, which defines international standards on light and colors.

2.17 COLOR COORDINATES

Because a color can be expressed in terms of three quantities (R, G, and B), it is possible to represent a color in three dimensions, as shown in Figure 2.72. In this representation, a color is represented by means of X,Y,Z coordinates, similar to using coordinates to represent a position in space. By replacing the X-, Y-, and Z-axes with R-, G-, and B-axes, the

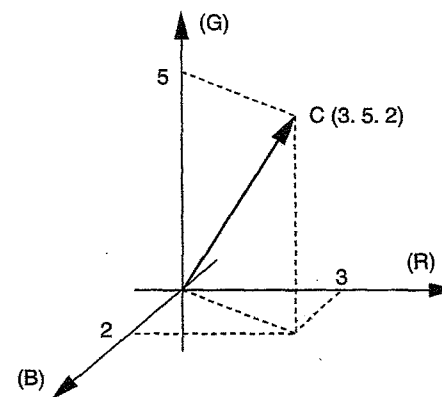


Figure 2.72 A three-dimensional representation of a color

color produced by mixing R,G,B in quantities 3,5,2, respectively, can be represented as the point (3,5,2) in RGB space.

Color has the property that different amounts of an RGB mixture only produce a change in brightness, without a change in color (hue and tone), as long as the ratio between R, G, and B is not changed. In other words, a color produced by mixing 1 part of R, 2 parts of G, and 3 parts of B is the same as that produced by mixing 3 parts of R, 6 parts of G, and 9 parts of B, producing only a difference in brightness. Therefore, let us express a color by setting aside, for the moment, the question of brightness. Let us normalize the tristimulus values (R, G, B), while keeping the ratio constant. To do this, we only need to perform the replacements shown in Equation 2.12:

$$\begin{aligned} R &\rightarrow R / (R + G + B) = r \\ G &\rightarrow G / (R + G + B) = g \\ B &\rightarrow B / (R + G + B) = b \end{aligned} \quad (2.12)$$

Thus, $r+g+b = 1$. The set r,g,b are called chromaticity coordinates. Since the expression $r+g+b = 1$ is the equation for a plane that passes through the three points (1,0,0), (0,1,0), and (0,0,1), the chromaticity coordinates are plotted on this plane. As shown in Figure 2.73, the coordinates (R,G,B) of a tristimulus value and the chromaticity coordinates (r, g, b) are two points that have the same direction from the origin but different distances from it.

Because any color can be produced by mixing the three primary colors in an appropriate ratio, by mixing RGB it is possible to produce the same color as a monochromatic color. Therefore, the CIE determined tristimulus values for the monochromatic colors that have the same energy value. These values describe an isochromatic function.

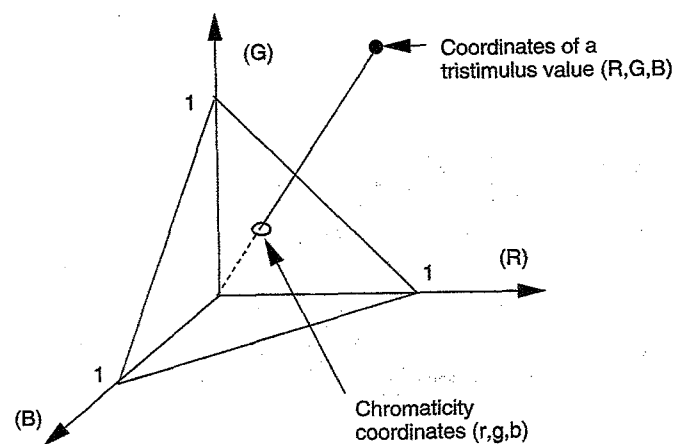


Figure 2.73 Relationship between a tristimulus value and chromaticity coordinates

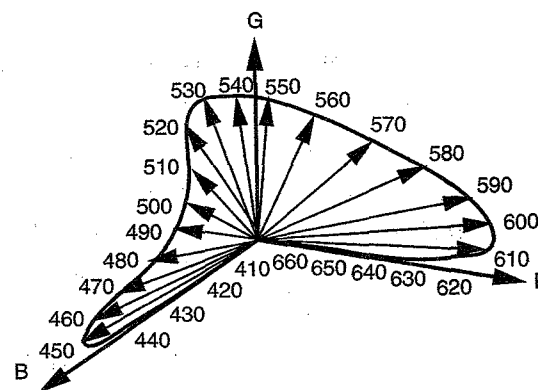


Figure 2.74 3D representation of monochromatic color tristimulus values of the same energy

Connecting the points representing monochromatic colors of equal energy results in the type of graph shown in Figure 2.74.

Figure 2.75 shows a re-plotting of Figure 2.74, in which the chromaticity coordinates of each monochromatic color are determined, and Figure 2.74 is viewed so that the R- and G-axes are visible and the B-axis is perpendicular to

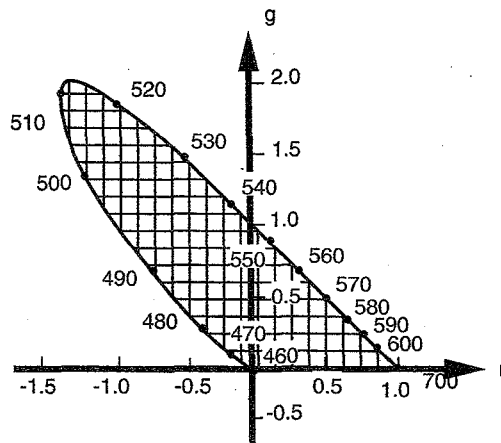


Figure 2.75 r-g chromaticity diagram

the paper on which the figure is graphed. This is called a chromaticity diagram. Since white is a mixture of the three primary colors in equal amounts, the white point is $(1/3, 1/3)$. Since (monochromatic) spectral colors are the colors that have the highest saturation of all colors, all colors that can be perceived by the eye fall within the curve formed by the points corresponding to the individual monochromatic beams. Since the lower the saturation of a color, the closer is the color to white, all other colors are closer to the white point than the saturated spectral colors are.

As mentioned above, the CIE expresses colors by using the spectral colors of wavelengths 700.0 nm, 546.1 nm, and 435.8 nm.

This is called the RGB color representation system. Another color representation system, the XYZ color representation system, is a mathematical modification of the RGB color representation system. Readers who would like to study the discipline of color should familiarize themselves with the x-y chromaticity diagram for the XYZ color

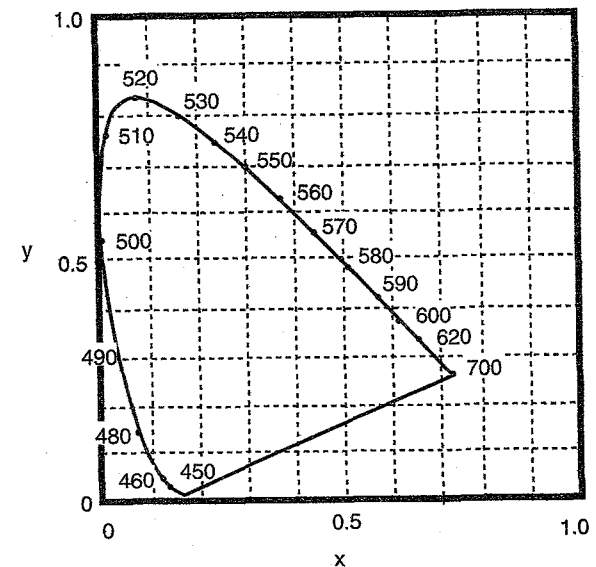


Figure 2.76 x-y chromaticity coordinates

representation system (Figure 2.76). Recently, $L^*u^*v^*$ and $L^*a^*b^*$ color representation schemes have also come into use. These schemes are designed to represent closely the way humans perceive colors.

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To recapitulate the foregoing discussion on color —

- (A) There are three attributes of color:
 - (1) hue, (2) saturation, and (3) brightness.
- (B) There are three primary colors that cannot be produced by other colors:
 - (1) red, (2) green, and (3) blue.
- (C) Any color can be produced by mixing the three primary colors (RGB).

Let us now turn to how to produce a color image on a liquid crystal display. To produce the maximum possible

number of colors, the primary colors can be mixed in wide variety of ways. As shown in Figure 2.77, if all colors are to be produced from one pixel in a screen, the pixel must contain the RGB primary colors. Therefore, the pixel is subdivided into three parts, in order to create windows (sub-pixels) from which RGB beams can be emitted. Once this is accomplished, any color can be produced by regulating the intensity of the RGB beams.

Because the RGB elements occupy physically different positions in a pixel, the reader might ask whether the colors can be perceived by the eye as a single color, rather than as three distinct colors. However, the human eye is not capable of distinguishing the individual RGB elements when they are packed in an extremely small area. To the human eye, these elements appear as a mixture of three colors. In Figure 2.78, the RGB colors are lined up alternately and the colors of the individual pixels are clearly distinguishable. However, as the size of a pixel is made increasingly smaller, the distinction between colors becomes increasingly blurred, and at a certain point the

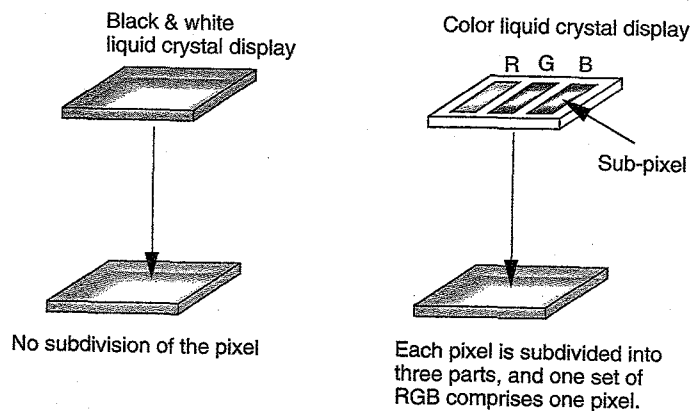


Figure 2.77 Comparison between black and white and color pixels

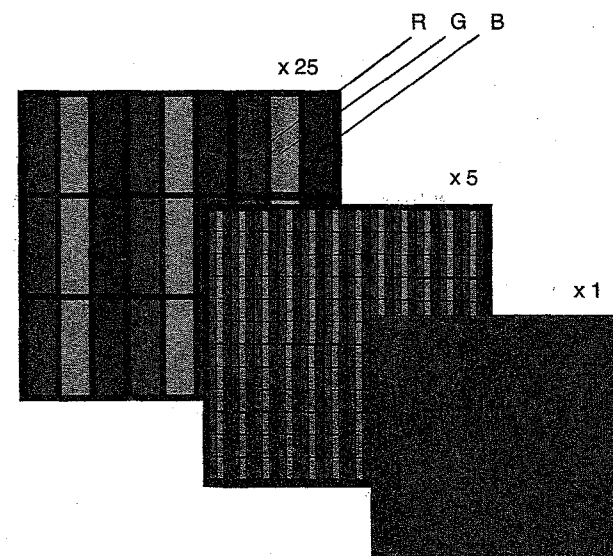


Figure 2.78 Minute RGB elements are not distinguished at normal viewing magnification

colors become totally indistinguishable. To ensure that the RGB beams emitted from the windows appear completely mixed, these windows must be extremely small. In the case of a panel that is viewed from a distance of approximately 30 cm, a window might measure approximately 300 μm vertically $\times$ 100 μm horizontally. In a display that is viewed from farther away, such as a TV display, the pixels can be significantly larger than the pixels that comprise a liquid crystal panel viewed from a shorter distance.

Let us now turn to the question of how to produce the RGB colors. As shown in Figure 2.77, since the liquid crystal itself does not emit light, a separate light source is required. Such a light source must be the source of white light that contains all the elements of RGB. In the case of light from a fluorescent lamp, for example, the color filter windows are made with special materials that admit the

passage of the RGB colors only, so that the R window transmits only the R light beam, and so forth. The array of windows is called a color filter. The brightness of a light beam is adjusted by opening and closing the liquid crystal shutters that are located underneath the windows. The opening/closing operations are performed by means of TFTs. By employing the structure of a liquid crystal panel and the TFTs that are incorporated in the panel as discussed in Section 2.8, it is possible to control the hue, saturation, and brightness on the screen. In this manner, virtually any color can be produced.

Another important consideration in producing color displays is the balance between the backlight and the color filter. The representative backlight for a color liquid crystal panel exhibits the type of spectral distribution shown in the upper portion of Figure 2.79. The color filters for the RGB pixels have the spectral transmittance distribution shown in the middle portion of Figure 2.79. The distribution is indicated by plotting, on the vertical axis, the percentage of the incoming light energy entering the color filter that is transmitted, i.e., light transmittance. The horizontal axis plots the wavelength. The red color filter, for example, transmits approximately 80% of the light longer than 620 nm in wavelength, while blocking all light components that are shorter than this wavelength. Thus, color filters are used to divide the backlight light beams into spectral components. To produce a color display, the RGB color elements obtained in this manner are mixed as required.

In actuality, the energies of the RGB primary colors after the light beam from a backlight source has passed through a color filter can be determined by multiplying the

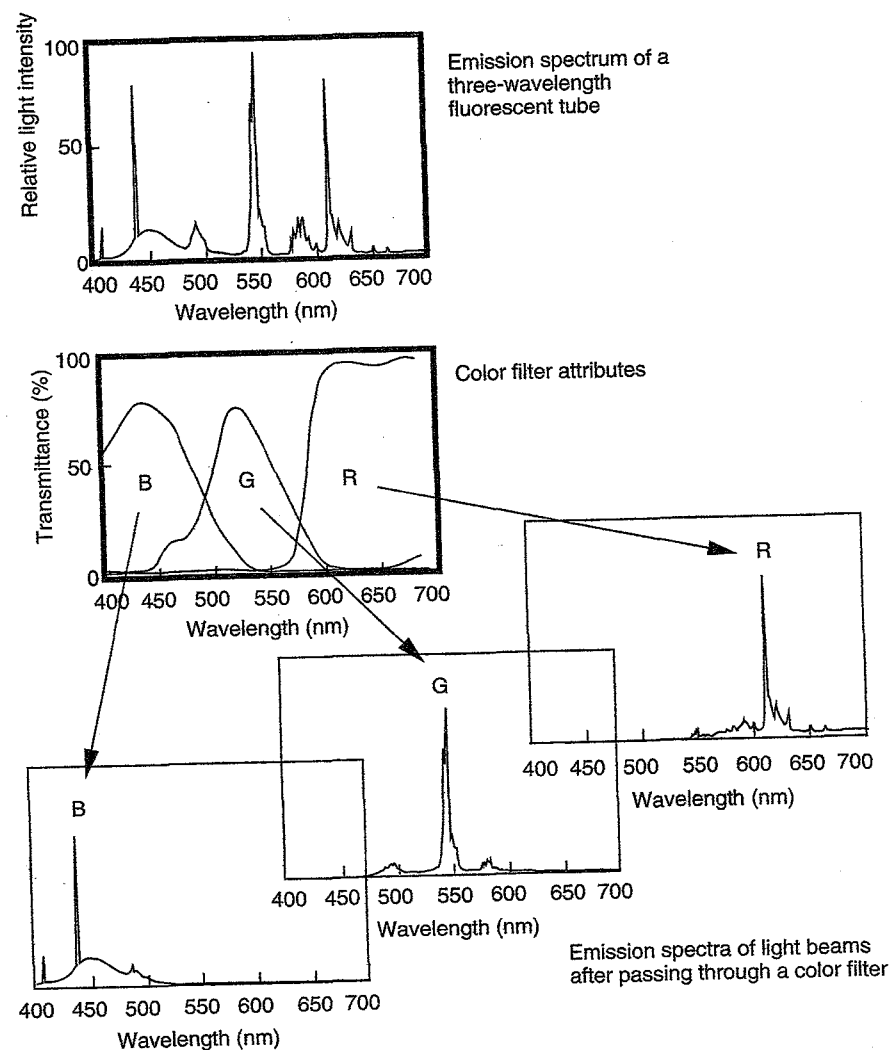


Figure 2.79 Emission spectra based on combinations of three-wavelength fluorescent tubes and color filters

transmittance of the color filter by the wavelength (bottom row, Figure 2.79). As shown in Figure 2.79, the beam emitted from the RGB pixel is not a monochrome beam, but it is a mixture of many wavelength components. Therefore, this

beam has a lower saturation than a monochromatic light beam. A high-saturation color cannot be produced by mixing colors of low tones. Therefore, on a color liquid crystal display it is not possible to produce colors that equal monochromatic light rays in saturation. This is a drawback that is shared by color TV and related display devices. An important consideration, however, is that, in order to display the most natural-looking colors possible, a judicious balance must be achieved between backlighting and the color filters. At present, it is technically difficult to produce bright colors by simply mixing monochromatic colors. Therefore, current research emphasizes achieving beautiful, more vivid colors by striking a happy balance between backlighting and color filters.

In another approach, primary colors that have certain wavelength bands are used in color liquid-crystal panels. The purpose of this technique is to facilitate the production of bright colors. Therefore, a great deal of research is being conducted in color liquid-crystal panel technology, with the result that among flat-panel displays, color TFT liquid-crystal panels are superior to the others in their ability to produce high-quality pictures.

2.19 FEATURES OF VARIOUS KINDS OF DISPLAYS

In this section, we discuss the relationship between the various concepts and topics that were touched upon in the preceding sections: liquid crystal materials, liquid crystal orientations, operating modes, and drive methods.

Figure 2.80 shows a mapping of those items. However, there are terminology issues. For example, "homeotropic liquid crystal" is a misnomer. Since the term refers to the

way a liquid crystal is oriented, the proper term should be "homeotropic orientation," to be distinguished from the names of materials (phases), such as nematic liquid crystal. The reader is cautioned that conventional names are used together with formal names. Therefore, a liquid crystal term should be understood by determining whether it is a term to classify a liquid crystal material, a liquid crystal orientation, an operating mode, or a drive method. Also, when a new liquid crystal is developed, it should be named according to its proper classification. At any rate, terminology confusion is something that one must accept. The important requirement is that we understand a given

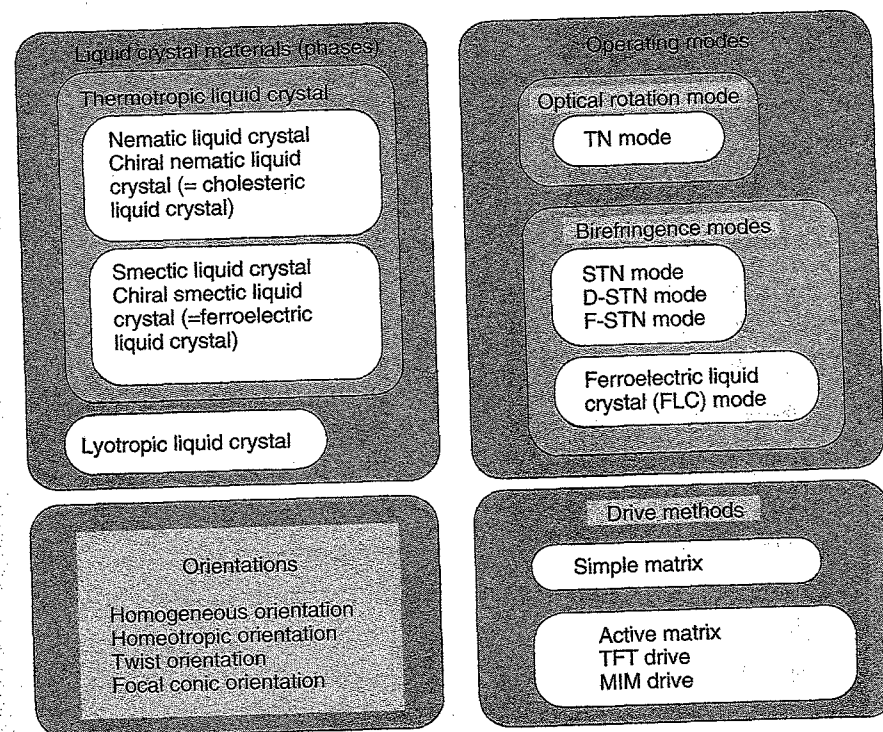


Figure 2.80 Names of liquid crystal elements and organizations

term in terms of its technical context. Also, we must be aware of the fact that often several terms are used to refer to the same phenomenon. Thus, simple matrix drive is called multiplex drive as well as passive matrix drive.

Table 2.1 summarizes the features and characteristics of liquid crystal panels. The lowest-cost liquid crystal panel is the simple matrix TN liquid crystal. Normally, the contrast ratio for a TN liquid crystal is greater than 100 when its drive method is a static drive. In the case of a simple matrix, however, the contrast decreases as a function of increases in pixel density. Therefore, suitable applications of simple matrix panels include displays used in telephones, wristwatches, and calculator segment displays, all of which are characterized by small display capacities. The FLC, being a simple matrix circuit, does not require complex active devices. On the other hand, from a production technology standpoint it requires a stringent surface flatness, which presents a considerable challenge in quality control and materials control in the liquid crystal panel assembly process. But as indicated in Table 2.1, the active matrix drive offers several advantages over the passive matrix drive in various evaluation items. Overall, the TFT liquid crystal panel offers superior performance in speed and display quality. Indeed, the TFT liquid crystal approach is essential to high-definition display devices, such as HDTV, viewfinders, and engineering workstations. MIM liquid crystal displays, on the other hand, are rivaling the TFT liquid crystal type in capabilities. In the future, the competition will intensify between increases in the quality of low-cost STN liquid crystal panels and decreases in the cost of high-quality MIM and TFT liquid crystals. At the present, cost decreases in TFT liquid crystals seem to

outpace the progress in the other direction. TFT liquid crystal panels are attracting considerable interest in the marketplace.

Historically, the development of actual liquid crystal panels began with the development of TN liquid crystals, with subsequent developments of other liquid crystals (Figure 2.81).

2.20 KINDS OF TFT LCDS

Several types of TFT LCDs exist for different applications. This section describes the types of TFT devices and traces the history of their development.

2.20.1 Design of a TFT

Initially, the development of CdSe-TFT and Te-TFT was explored; however, these TFTs gave way to silicon-based

Table 2.1 Liquid Crystal Displays and their characteristics

Item	TN	STN	FLC	MIM	TFT
LC material	Ne	Ne	SmC*	Ne	Ne
LC orientation	Twist	Super-twist	Homogeneous	Twist	Twist
Twist angle	90°	240-270°		90°	90°
Mode	TN opt. rotation	STN birefringence	FLC birefringence	TN opt. rotation	TN opt. rotation
Drive method	Simple	Simple	Simple	Active	Active
Active device	-	-	-	MIM	TFT
Contrast ratio	10	20	20	80	100
Threshold characteristic	-	-	-	-	-
Response speed	-	-	-	-	-
Gap deviation (μm)	0.3	0.05	0.05	0.1	0.1
Application	Watches, calculators	PCs, word processors	EWS	PCs, TVs, VFs	PCs, TVs, VFs

Ne: nematic liquid crystal
VF: view finder

SmC*: chiral nematic C liquid crystal
EWS: engineering workstation

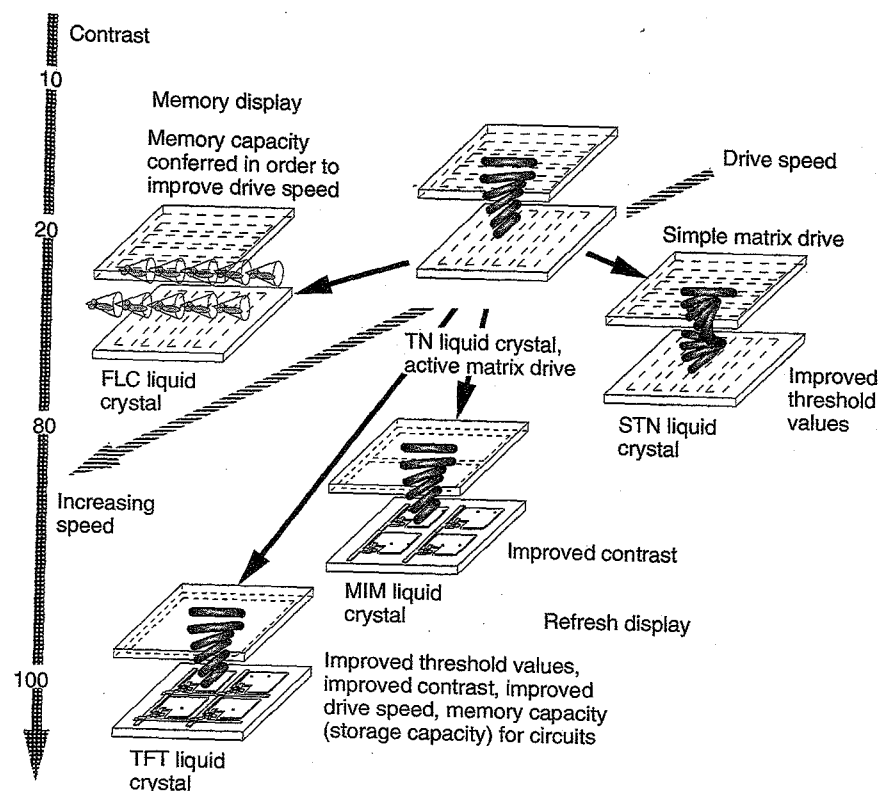


Figure 2.81 LC panel development trends

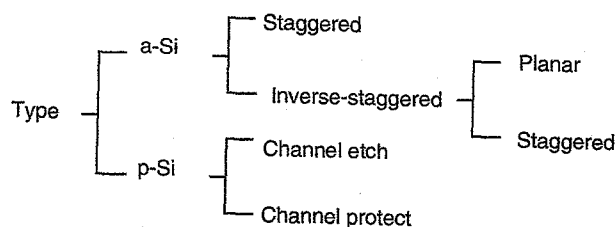


Figure 2.82 Kinds of TFTs

TFTs because of problems of reproducibility and large off-current. The thin-film silicon TFT formed from a deposited silicon layer, was developed because bulk silicon is an opaque substance which does not transmit visible light. In TFT technology, transistors are formed on a transparent glass or quartz substrate. This line of research led to the development of polysilicon (p-Si) TFTs and amorphous silicon (a-Si) TFTs. Although it is costly to produce and is difficult to fabricate in large areas, the p-Si TFT possesses an electron mobility that is one or two orders of magnitude larger than the a-Si TFT. This makes the p-Si TFT a good candidate for the fabrication of small, high-definition displays, such as viewfinders and projection displays. On the other hand, the a-Si TFT is amenable to fabrication in large areas and in low-temperature processes (300°C-400°C). Therefore, it is used in pocket TVs and notebook PCs.

(1) a-Si TFT

The a-Si TFT can be fashioned in two structures: staggered and inverse staggered, shown in Figure 2.83. As the figure indicates, the staggered-type has a top-gate structure, whereas the inverse-staggered-type has a bottom-gate structure. Although these are basically upside-down structures of each other, each requires special design considerations.

Amorphous silicon, a-Si, is often used in solar cells. When light strikes the a-Si, the resulting photoelectric conversion generates a photocurrent. Because this phenomenon can cause malfunction in the panel that incorporates the a-Si TFT, the a-Si layer must be as thin as possible. Beyond that, the a-Si TFT must be shielded from incident light by some means. Therefore, the staggered structure is provided with a special shielding film underneath the a-Si.

By contrast, for the inverse-staggered structure, an a-Si thin-film is formed first, followed by the formation of drain and source electrodes. The process of forming a thin-film by plasma CVD (Chemical Vapor Deposition) and sputtering, and dry (plasma) etching processes, can cause damage to the a-Si thin-film. An a-Si thin-film can be etched either directly (channel-etching) or by forming a protective film on the a-Si thin-film (channel-protect-etching). The channel-etching method is susceptible to problems of overetching of the a-Si film. The method requires the etching of the ohmic layer (n^+ a-Si) in the channel region, which can cause etching of the underlying a-Si film to some extent. On the other hand, the method offers the advantage of producing more stable performance characteristics.

Each method has its own set of advantages and disadvantages. However, because the inverse-staggered structure offers an electron mobility that is 30-40% larger than the staggered type, and less damage from the effects of plasma processing, the two inverse-staggered structures shown in Figure 2.83 are widely used in 10-inch color LCDs.

(2) *p*-Si TFT

Because it employs polysilicon, p-Si, the p-Si TFT has an electron mobility one or two orders of magnitude larger than a-Si. p-Si TFT products that are made using high-temperature LSI processes (1000°C) require the use of an expensive quartz substrate. Consequently, in terms of cost, the p-Si TFT cannot easily be made in large areas. However, because the TFT devices can be reduced in size, p-Si TFTs can be fashioned with a high aperture ratio. This

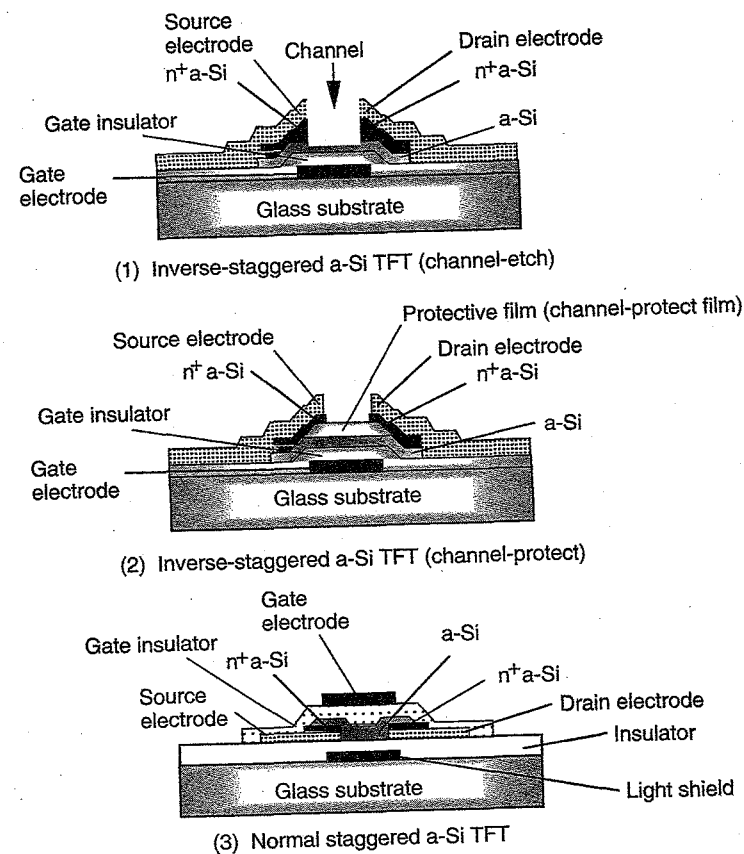


Figure 2.83 Types and structures of a-Si TFT

makes the p-Si TFT a good candidate for the production of small, high-density devices (1.7-4 inches), such as viewfinders and HDTV projectors.

These TFTs are fashioned in planar structures, shown in Figure 2.84. Because these structures entail complex fabrication processes, p-Si TFTs are mostly used in applications that demand the highest possible reliability.

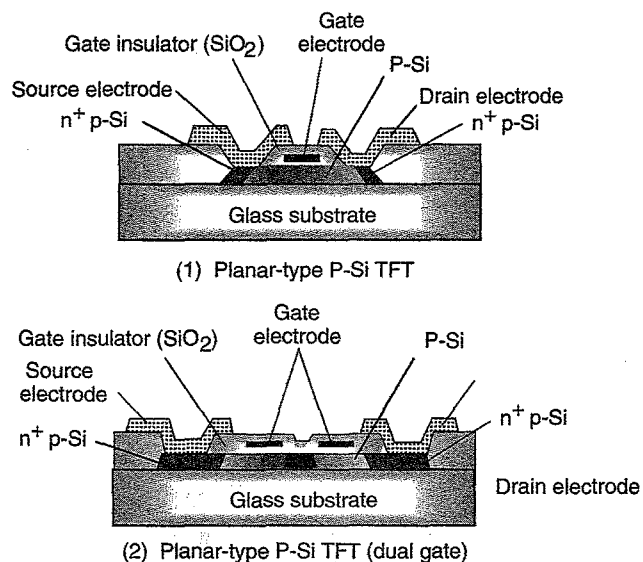


Figure 2.84 Structure of a p-Si TFT

2.20.2 Applications of TFT LCDs

This section explains applications of color TFT displays. As shown in Figure 2.85, there are two major types of display methods:

(1) Direct View

Direct-view panels are used in pocket TVs and notebook PC displays. A critical requirement is the viewing angle attribute, so that the display can be viewed from any angle. In contrast to a monochrome display, variability in color is also an important consideration. The human eye is very sensitive to the presence of defects. The eye can detect a contrast ratio difference of 5 between adjacent pixels, a color difference (ΔE_{ab}) of 3, and defects as small as 20 μm . Consequently, displays are subject to stringent performance requirements. Direct-view panels are produced in

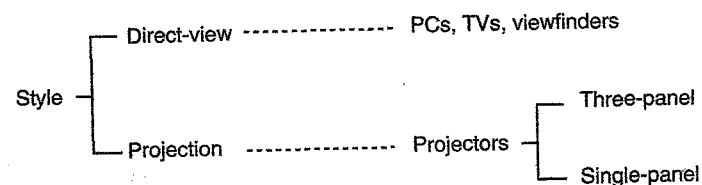


Figure 2.85 Applications of color liquid crystal displays

several size ranges: viewfinder size (1-2 inches), pocket TV size (3-6 inches), notebook PC size (8-10 inches), and EWS monitor size (14-20 inches), as shown in Figure 2.86. All these products use color filters to control the amount of transmitted light for each of the primary colors, so that three pixels form one unit of display.

(2) Projection

Three types of projectors are available in the marketplace: front projectors, which project onto a screen; rear-projectors, which project from the back of the projection unit; and overhead projectors (OHPs).

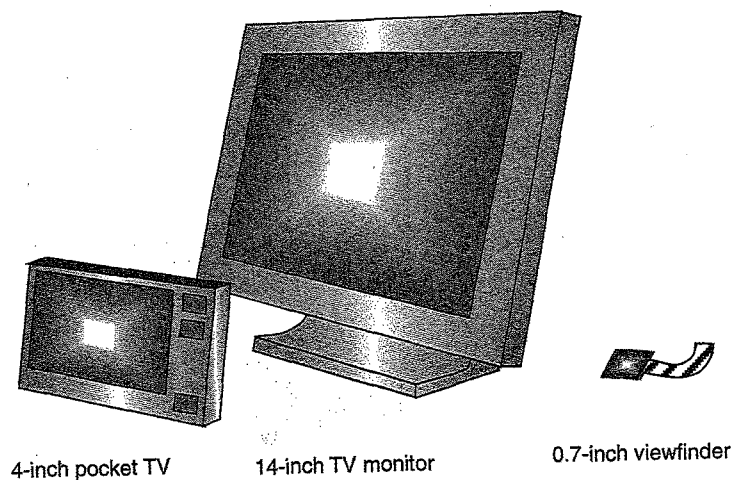


Figure 2.86 Applications of direct-view TFT LC panels

The front projector, Figure 2.87, uses a powerful metal halide lamp (1,000,000 lux as measured on the panel) to project images formed on a 3-5-inch LCD panel onto a screen 40-200 inches in size. Figure 2.88 shows the emission spectrum of a metal halide lamp. With a color temperature of 7,000°C-10,000°C, the lamp has a high proportion of the white spectral component. Whereas the three-band fluorescent lamp has only three wavelengths, which correspond to the RGB primary colors, the metal halide lamp can produce continuous wavelengths. Despite the powerful light source, however, the resulting light intensity on the projection screen is only about 1,000 lux. Therefore, pictures from a projection unit must be viewed in a dimly lit room, as in a movie theater.

Figure 2.89 shows a rear-projection unit. This unit uses a metal halide lamp for a 3-5-inch LCD panel. Images are projected from the rear of a 40-60-inch screen by means of mirrors (Figure 2.90). Because of their compact size, rear-projection units are used in 50-inch class TV sets.

In an overhead projector, a 10-inch color LCD is set on top of a metal halide lamp OHP, and images are projected onto a screen. This allows a motion picture display for powerful presentation effects, a capability not present in

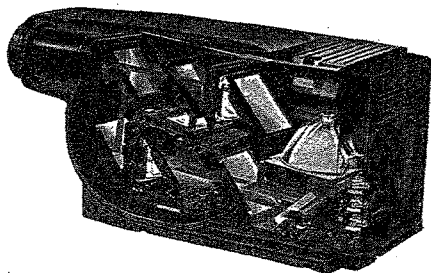


Figure 2.87 Front projector

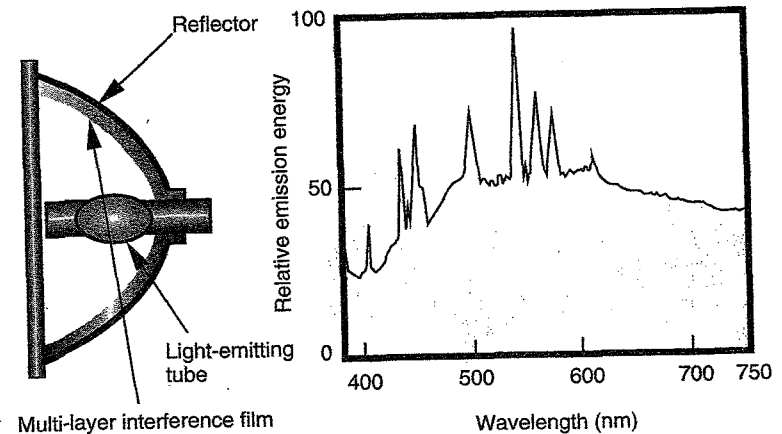


Figure 2.88 Structure of a metal halide lamp and the emission spectrum

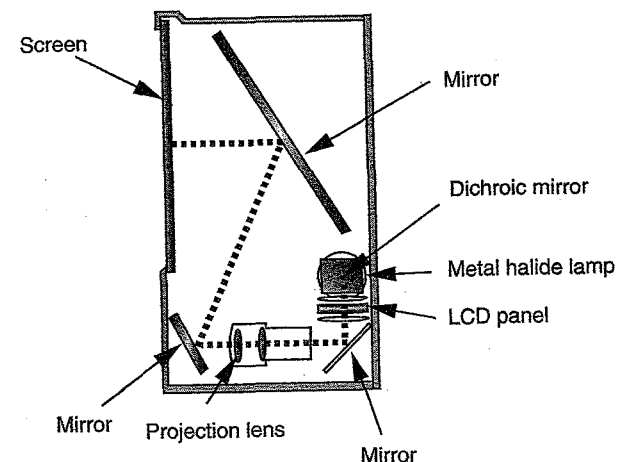


Figure 2.89 Structure of a rear projector

presentations with OHP foils. OHPs are designed for scientific and business presentations. In contrast to the conventional foil-based OHP, which requires that the hardcopy to be projected first be copied onto a transparent foil, an attractive feature of the LCD-based OHP is that computer graphics can be projected directly from the source computer.

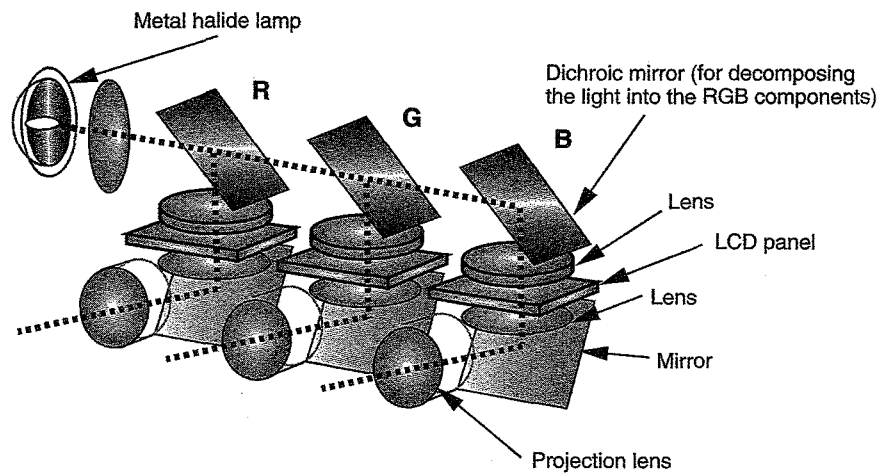


Figure 2.90 Optical system for a rear projection unit

There are three-panel and single-panel LCD-based OHPs designed to produce color. Figure 2.91 shows a schematic diagram of the optical system for a three-panel front projector, which uses three TFT arrays. This system uses a dichroic mirror to split the light beam from a light source into RGB components. The components are passed through their respective LCD panels, and recombined at the final step. In this manner, color images can be projected onto the screen. As shown in Figure 2.92, the dichroic mirror is composed of a multi-layer film of inorganic thin-films. Figure 2.93 shows the excellent spectral resolution characteristic of this mirror. The level of resolution that can be produced by a dichroic mirror is significantly superior to that available with dye-based color filters. A drawback of the dichroic mirror approach, however, is high cost.

Aperture is an index of pixel performance characteristics. Aperture refers to the proportion of the effective display area of the pixels through which light can actually

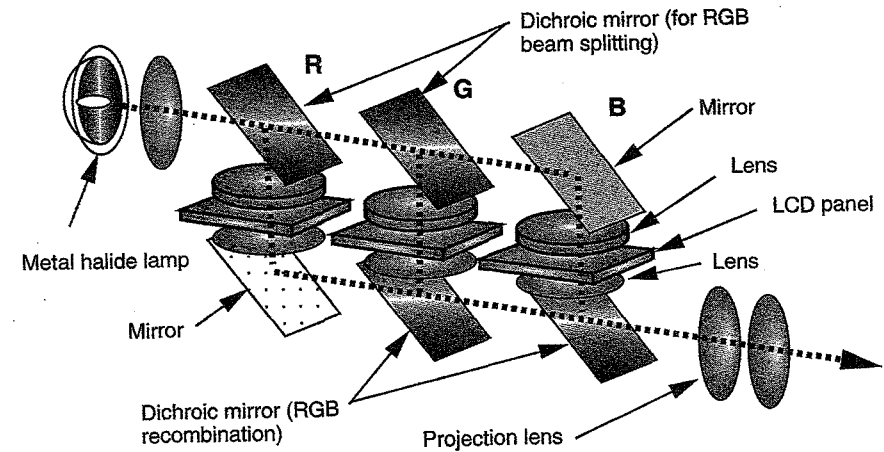


Figure 2.91 Structure of a three-panel TFT LCD projector

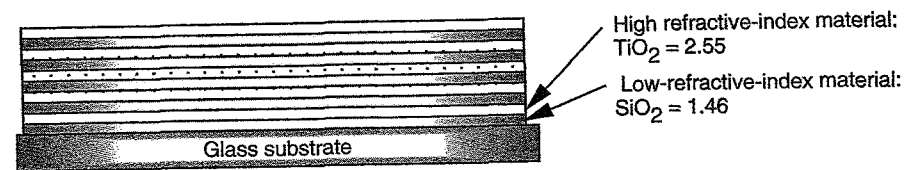


Figure 2.92 Laminated structure of a dichroic mirror

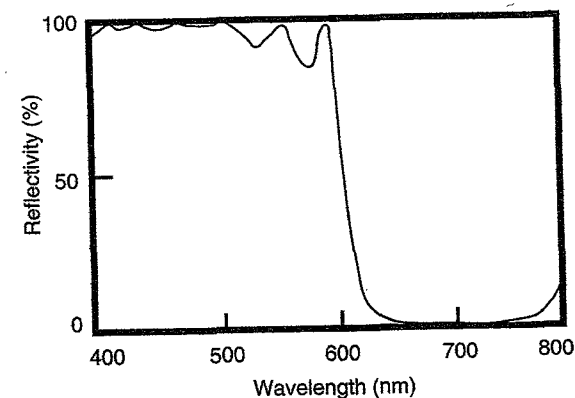


Figure 2.93 Reflection characteristics of a dichroic mirror

pass, in a unit area of repeating pixels. The smaller an LCD, the larger the proportion of the area occupied by the TFT relative to a unit area of repeating pixels. In the case of the aperture for the three-panel system, a pixel is split into three RGB components by a mirror, the transmittance is controlled for each color, and then the color components are recombined. In such a three-panel system, a pixel can occupy three times more area than in the case of the single-panel system (color filter system) depicted in the figure below. Figure 2.94 illustrates this fact. Thus, a three-panel system allows displays that are three times more dense than the single-panel system can.

Figure 2.95 shows the optical system for a single-panel projector. This system uses a color filter to produce the individual RGB pixels, and projects images onto a screen using the same technique as the direct-view system. A salient feature of this system is that it requires only one TFT panel to display all images, thus reducing the cost of the optical system to one-third the cost in a three-panel system. However, with only one TFT array, the single-

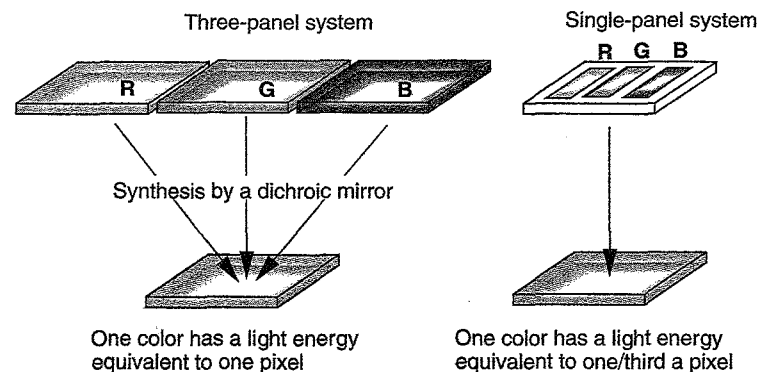


Figure 2.94 Comparison of single-panel and three-panel apertures

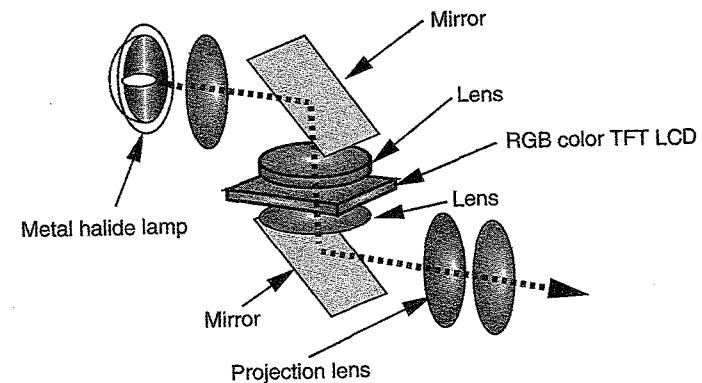
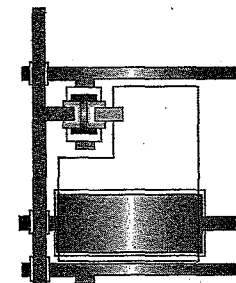


Figure 2.95 Structure of a single-panel TFT LCD projector

panel system can produce only one color per pixel, compared with the three colors per pixel location that can be produced by a three-panel system. Therefore, the resulting picture quality is lower.

Thus, compared with the single-panel system, the three-panel system offers advantages in superior picture quality and brightness, at the expense of increased complexity of the optical system, including the dichroic mirror. This translates into higher cost.



CHAPTER 3

STRUCTURE OF COLOR TFT LIQUID CRYSTAL DISPLAYS

3.1 MANNER OF CONSTRUCTION

LCD panels come in various formats, depending on the manner in which they are constructed and the application for which they are intended. Among these, the direct-view LCD panel using a-Si TFT (amorphous Silicon Thin-Film Transistor) is most widely used. Commercially, they are available in various products, ranging from 3-inch pocket TVs to 10-inch notebook personal computers. This section discusses in detail this type of color TFT LCD panel.

There are several reasons that color TFT LCD panels are used as display devices: the color TFT LCD panel offers a greater range of colors than any other type of display while producing higher contrast. Further, they are smaller, lighter, and extremely low in power consumption.

Beyond their performance characteristics, production yield improvements account for the speed with which these panels have made inroads. The cornerstone technology that has helped to improve production yields has been cleanliness-control in the fabrication process.

Let us now discuss, with reference to examples, some of the technical hurdles that had to be overcome in order to achieve an adequate degree of cleanliness control.

In the fabrication of semiconductor devices, if 100 IC chips are to be produced on a wafer that is 20 cm in diameter, and a 0.1 μm dust particle occurring on the wafer damages three ICs, the three affected IC chips can be discarded as defective chips, leaving 97 chips intact. This gives a yield of 97%. In the case of a TFT LCD panel, however, in some situations dust particles up to 1 μm in size can be tolerated as long they do not cause the circuits to short. However, any larger dust particle, even just one, that intrudes into the display area can render the entire panel defective. In the case of a 10-inch panel, it is necessary that not a single dust particle greater than 1 μm in size occur in the entire glass substrate measuring 300 mm $\times$ 200 mm. This means that an LCD panel requires a completely dust-free area several times larger than in the case of a semiconductor wafer. Therefore, LCD panels require more stringent cleanliness control, albeit in a different sense, than the semiconductor device does. Because dust particles can cause line breakage, pinholes, and myriad other types of defects, actual production is possible only if the manufacturing process involved is a simple, reliable one.

On another note, the advent of a-Si technology has lowered the array substrate-processing temperature in the TFT fabrication process to about 300-350°C. This has been a key event that has made TFT fabrication an industrially viable process. Since p-Si (polycrystalline Silicon) requires high-temperature processing in the range of 1000°C, it can only use quartz as the glass substrate. By contrast, a-Si can use a non-alkaline glass (white plate glass) that has a soft-

ening point at 600°C. Although the low-cost soda lime glass (green-plate glass) that has been used extensively for STN panels cannot be used for TFT, the non-alkaline glass has been able to reduce the substrate glass material cost by a factor of ten from quartz glass. This has helped to achieve greater precision in feature size, lower production cost, and greater cleanliness. The cost reduction has enabled the TFT technology to meet various production standards and has opened the way to the mass production of 10-inch TFT LCDs.

This section discusses the a-Si TFT LCD.

3.1.1 Module Construction

Figure 3.1 shows the structure of a color TFT LCD module. Whereas two glass substrates with a liquid crystal between them is referred to as a panel, when a driver LSI and illumination devices (backlight) are added as peripheral materials, it is called a module. Thus, a module is an LCD with pins that connect to the system. A module is a subsystem

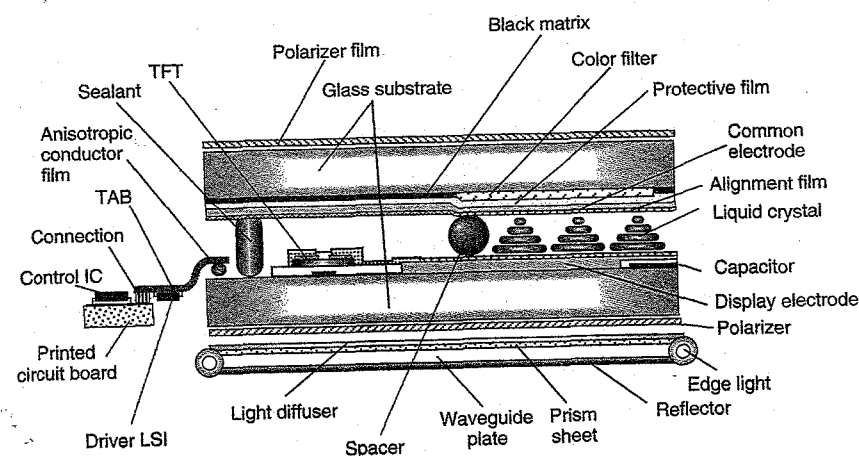


Figure 3.1 Cross-section of the color TFT LCD

which can display characters and pictures simply by being connected to the system. Figure 3.1 also provides the nomenclature of the components comprising a module. Although a detailed explanation will be given in Section 3.4 and later, this section simply describes the function of the components.

<i>Polarizer film</i>	This film either transmits or absorbs a specific component of polarized light.
<i>Glass substrate</i>	This is a transparent substrate for an LCD. It is a non-alkaline glass with a low surface irregularity, with ideal peak-to-valley distortion of less than 0.05 μm .
<i>Black matrix</i>	This is a light-shielding film that is provided between pixels in a color filter.
<i>Color filter</i>	This is a resin film containing three-primary-color (red, green, and blue) dyes or pigments.
<i>Protective film</i>	This film is designed to protect the color filter. In some applications, the protective film is coated with a silica film in order to enhance its adhesion to the ITO film.
<i>Common electrode</i>	This is an electrode made with a transparent, electrically conducting indium-tin-oxide (ITO) film.
<i>Alignment film</i>	This is an organic thin film, usually made of polyimide, designed to align the liquid crystal.
<i>Liquid crystal</i>	To achieve desired performance characteristics, liquid crystals are made by blending several types of nematic liquid crystals.

<i>Spacer</i>	A spacer is composed of either silica or resin particles, designed to regulate the thickness (cell gap) of the liquid crystal layer of an LCD panel (cell).
<i>Sealant</i>	This is a bonding agent for fixing a TFT array substrate onto a color filter array substrate around the edges of the substrates.
<i>Sealing agent</i>	This chemical is used to seal the inlet through which liquid crystals are injected.
<i>Display electrode</i>	This is a transparent, electrically conducting electrode that functions as a picture element for displaying images.
<i>TFT</i>	This is a switching device that drives the liquid crystal.
<i>Capacitor</i>	This is a signal-retaining capacitor that provides active matrix driving.
<i>Edge light</i>	This is an illumination device, usually a cold cathode fluorescent tube.
<i>Reflector film</i>	The reflector film enhances light utilization efficiency by reflecting the edge light not directed toward the panel surface to the panel.
<i>Diffuser film</i>	The dispersion film uniformly directs the edge light onto the LCD panel.
<i>Prism sheet</i>	This component increases the brightness of the light that is transmitted directly from the panel surface.
<i>Waveguide film</i>	This film guides the edge light onto the entire LCD panel surface.
<i>TAB</i>	This is a flexible interconnect substrate on which driver LSI chips are mounted.

Driver LSI	This is an LSI chip that drives a liquid crystal through a TFT.
Anisotropic, conducting film	This is an adhesive, conducting film that is used to electrically connect the TAB to an LCD panel.
Printed circuit board.	This is an interconnect board that incorporates IC chips for converting display information into display signals.

3.1.2 Color TFT Panel Construction

Figure 3.2 shows the structure of a color TFT LCD. The nomenclature of the components of this figure is the same as that presented in Figure 3.1. The names of the components of the thin film transistor are given in Figure 3.3.

A TN-TFT LCD panel is fabricated starting with a TFT glass substrate, containing the TFTs, capacitors, and interconnect wiring; and a color filter substrate, which is made by forming a color filter on a glass substrate. These glass components are joined with a sealant. Liquid crystal material is then injected into the gap between the substrates, and the injection inlet is sealed with a suitable sealant. A

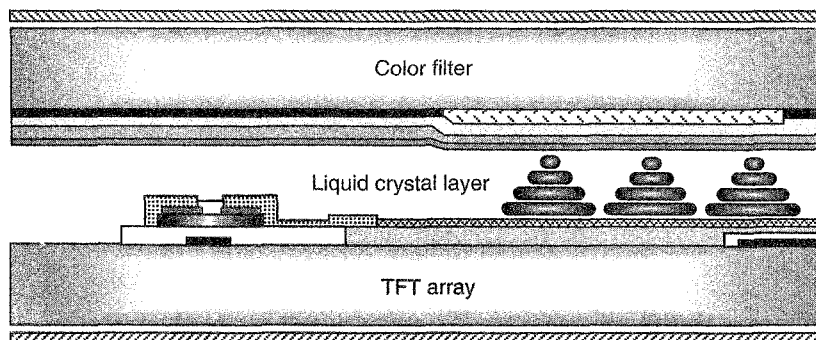


Figure 3.2 Structure of a color TFT LCD

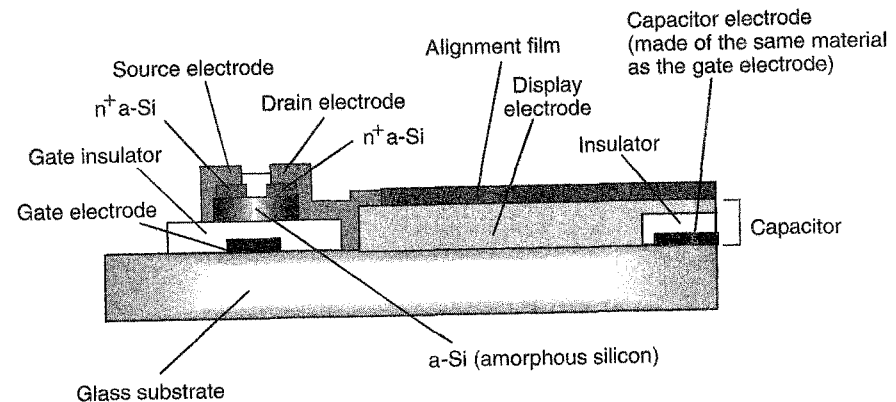


Figure 3.3 Cross-section of TFT array and pixel structure

critical requirement in this fabrication process, from the standpoint of ensuring high-quality display, is the optimum design of the cell gap. As was touched upon in Chapter 2, careful control of the cell gap must be maintained for the normally black display mode in TN liquid crystals.

In a TN liquid crystal, the only difference between the normally black mode and the normally white mode lies in the orientation of polarizer films used: the parallel Nicol film vs. the cross-Nicol film. Figures 3.4 and 3.5 show the relationship between contrast and retardation (defined as $\Delta n d$) in the normally black mode and in the normally white mode, respectively.

As indicated in the Figure 3.5, the normally white mode suffers from a rapid decline in light transmission when the retardation, $\Delta n d$, falls below the $0.48 \mu\text{m}$ level. The reason is that a retardation less than $0.48 \mu\text{m}$ causes an appreciable amount of light leakage. This can be seen from the relationship between the change in retardation and the change in light transmittance in the normally black mode,

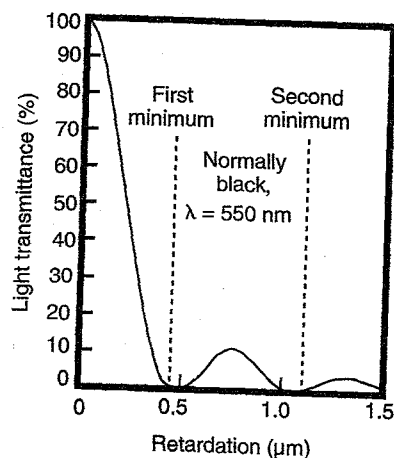


Figure 3.4 Relationship between retardation and light transmittance in the normally black mode

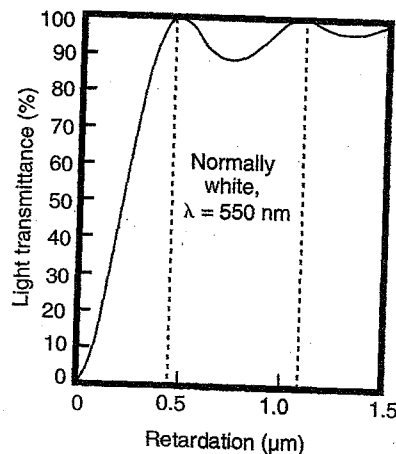


Figure 3.5 Relationship between retardation and light transmittance in the normally white mode

as depicted in Figure 3.4. As shown in Figure 3.4, the first minimum occurs when the retardation is $0.48 \mu\text{m}$ at the 550 nm wavelength. A retardation less than this value causes a rapid increase in the amount of light leakage. Also as shown in Figure 3.4, to obtain the maximum contrast the retardation should be set to $1.1 - 1.3 \mu\text{m}$, in the neighborhood of the second minimum. However, in this retardation range the viewing angle declines. Therefore, normally-black-mode LCD panels are designed so that their retardation occurs at the first minimum, or at a value slightly less than $0.48 \mu\text{m}$ in order to address other performance requirements.

The normally white mode, on the other hand, exhibits a transmittance relationship which is the inverse of the relationship for the normally black mode, so that the contrast reaches a maximum when the retardation, $\Delta n d$, is at

$0.48 \mu\text{m}$. Furthermore, for displaying black in the normally white mode, the liquid crystal exhibits little birefringence. Therefore, the black displayed in the normally white mode is the black color of the polarizer film. This true black, which does not require fine adjustments, excels in contrast. For this reason, most color TFT LCDs employ the normally white mode. One drawback of this mode, however, is that displaying black requires a continuous application of voltage, thus resulting in increased power consumption. Even with this shortcoming, the normally white mode is favored because of a superior picture quality.

As the foregoing indicates, both for the normally black mode and the normally white mode, a retardation in the vicinity of $0.4 - 0.5 \mu\text{m}$ appears to be appropriate from the standpoints of contrast and viewing angle.

Another important consideration in the design of an LCD panel is the electrical resistance of the liquid crystal material. In electrical terms, the color TFT LCD panel can be viewed as a capacitor which is held between a TFT array substrate and a color filter substrate. The upper electrode is a common electrode, the liquid crystal is an insulating substance that functions as a capacitor, and the lower electrode is a display electrode that is connected to the TFT. The equivalent circuit of the color TFT LCD panel consists of a parallel connection between condensers and resistors, as shown in Figure 3.6. A low resistance value causes a rapid discharge of the electrons accumulated on the liquid crystal capacitor via the TFT. Therefore, the liquid crystal needs to be purified so that its resistivity is in the order of $10^{12} - 10^{13} \Omega\text{-cm}$. The manufacturing process must be strictly controlled so as to minimize the amount of impurities, such as ions, entering the liquid crystal.

Driving a liquid crystal involves changing the orientation of the liquid crystal by charging and discharging the liquid crystal capacitor that is held between a display electrode and a common electrode, as depicted in Figure 3.6. The drive velocity of a liquid crystal mixture is equal to the speed at which the orientation of the liquid crystal changes as a function of charging and discharging actions. Commercially available LCDs are designed with an optimal combination of various liquid crystals to suit a given operating mode. The typical drive speed, expressed as the response time required of the liquid crystals that are incorporated into commercial products, is 20-50 ms. Various types of LCDs, including low-speed remote controllers and calculators, and high-speed HDTV and multimedia display units, are included in this drive speed range. Research on factors that affect the speed of a liquid crystal indicates that the viscosity of the liquid crystal is a critical factor. Investigations conducted at various laboratories on low-viscosity materials have led to the development of new, fluorinated liquid crystal materials, which have attained a fast response time of 20 ms.

Another important requirement in the preparation of a liquid crystal is the selection of polar groups in the liquid crystal molecule. Polar groups have a large bearing on the birefringence that is exhibited by the liquid crystal. The polar groups in a liquid crystal, on the other hand, are also closely related to the viscosity, the elasticity coefficient, and to other properties of the liquid crystal. Since no single liquid crystal can satisfy all performance characteristics that are required of an LCD, the desired set of performance criteria, including the birefringence and the response speed, is met by blending various types of liquid crystals.

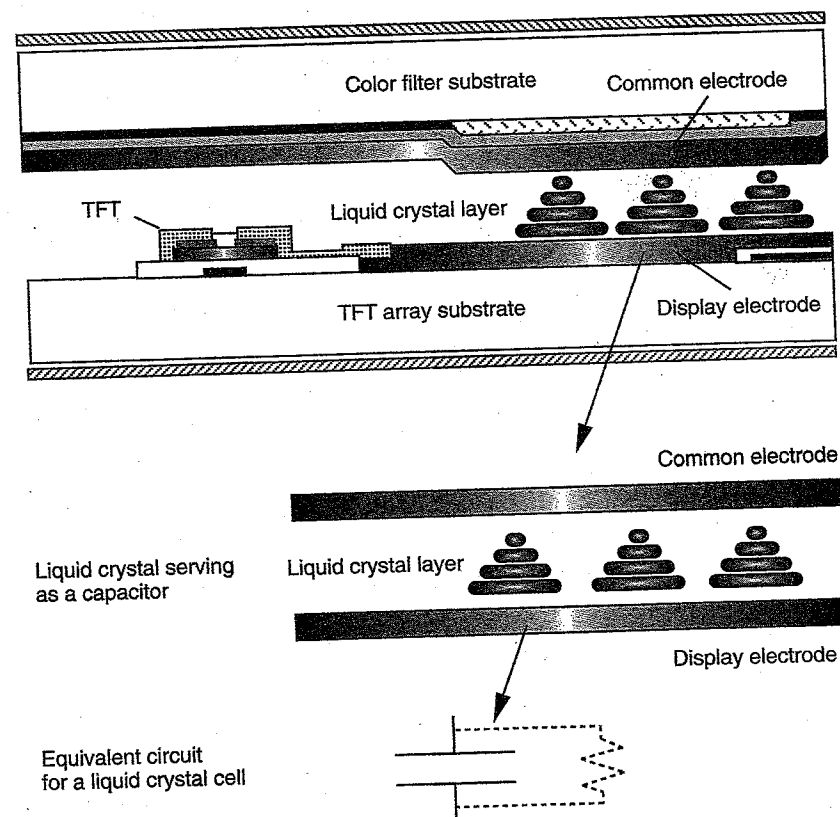


Figure 3.6 Equivalent circuit for a liquid crystal

Let us now turn to the structure and design of a TFT array. A TFT has three electrodes: gate, source, and drain electrodes. Following is a detailed description of these electrodes with reference to equivalent circuits.

As shown in Figure 3.7, current flows either from the source electrode to the drain electrode or from the drain electrode to the source electrode. During this current flow, the gate electrode performs the function of either admitting or blocking electrons. Thus, when a voltage is applied to the gate electrode, the resulting electric field causes the electrons, until now dispersed in the a-Si, to navigate to

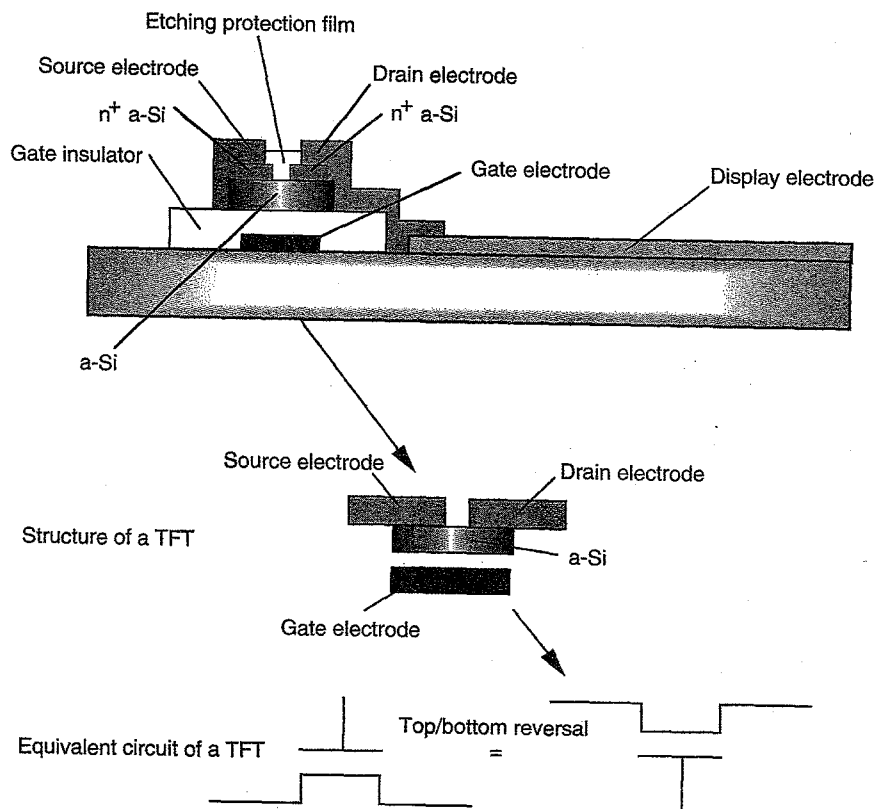


Figure 3.7 Equivalent circuit of a TFT

either the source or drain electrode. This induces the activation of an electron channel and leads to the migration of electrons between the source and drain electrodes. This type of transistor, which controls the flow of current by means of electric fields, is called the field-effect transistor (FET). The TFT, which is a thin-film transistor, is functionally a type of FET. The design of the TFT is the most critical factor in determining the quality that can be attained by an LCD panel.

In addition to the TFT, another device that performs an important function in the LCD panel is the capacitor. With

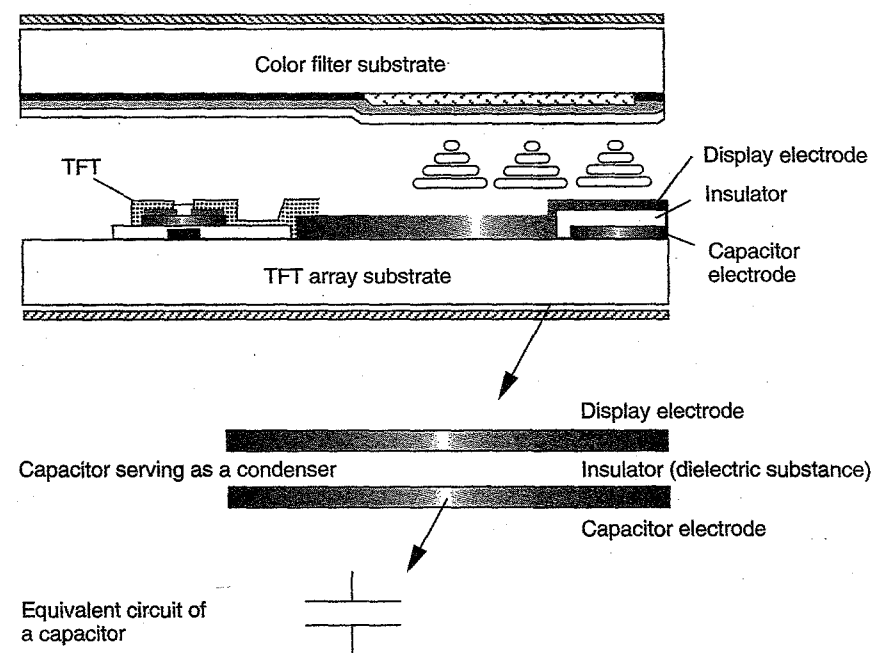


Figure 3.8 Equivalent circuit of a capacitor

only a TFT attached to it, the charge applied to switch the liquid crystal leaks away after only a brief time after a signal arrives. Therefore, it is necessary to connect an additional capacitor to the liquid crystal so that the liquid crystal is able to retain the charge associated with the first signal until a second signal is received. A capacitance can be conferred on a liquid crystal either by using an adjacent gate electrode line or, as illustrated in Figure 3.8, by forming a capacitor that is independent of the gate electrode. This section focuses on the latter type of capacitor. As shown in Figure 3.8, when a gate electrode is formed, a capacitor electrode independent from the gate electrode is also formed. By using this electrode as one of the pair of

electrodes and by using part of the display electrode as the other member of the pair, a capacitor is formed.

As the foregoing indicates, interconnecting the three constituent elements (liquid crystal, TFT, and capacitor) results in the circuit shown in Figure 3.9, which is an equivalent circuit representing a pixel. In addition to the three elements (liquid crystal, TFT, and capacitor), color filters and other peripheral elements also need to be incorporated. These additional elements will be discussed in sections beginning with Section 3.4.

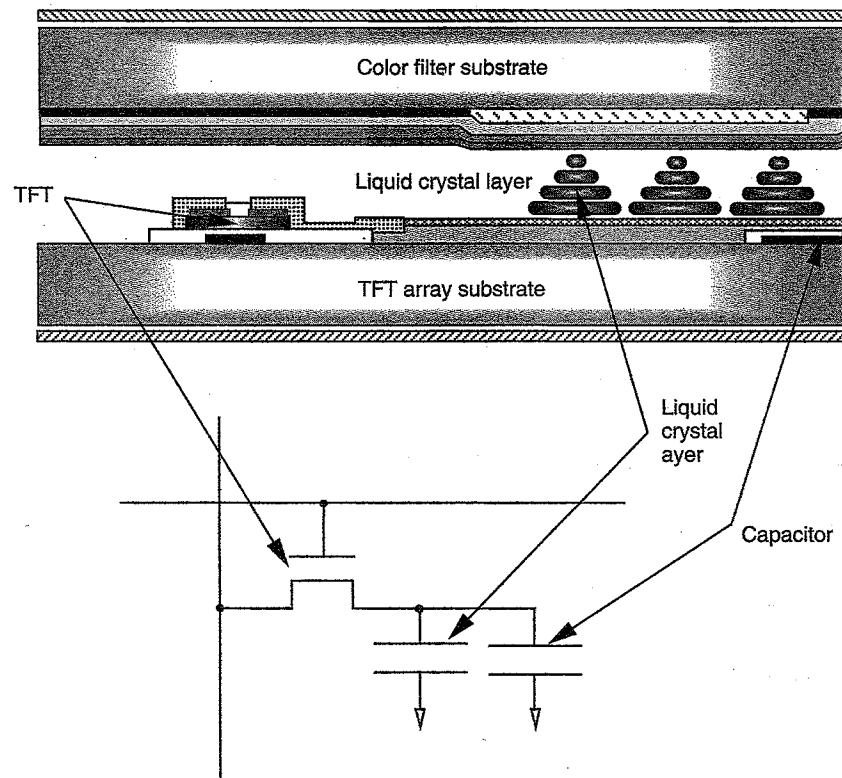


Figure 3.9 Equivalent circuit for a TFT that corresponds to one pixel

3.1.3 Driving a TFT Array

An actual TFT LCD panel contains, for example, 640x3x480 TFT devices. Space does not permit describing the driving principles of all pixels by drawing their equivalent circuits. Therefore, in what follows we explain how 3x3 pixels are driven.

Figure 3.10 shows a 3x3-pixel equivalent circuit. As indicated, the gate and source electrodes are used on a shared basis in various rows and columns. However, there is only one possible combination for a given gate electrode and a source electrode. To drive pixels from among the nine TFT pixels to form pictures and characters based on these operating principles, the gate electrode wires are scanned by time division, as in the case of the passive matrix. For example, when the second (selected) gate

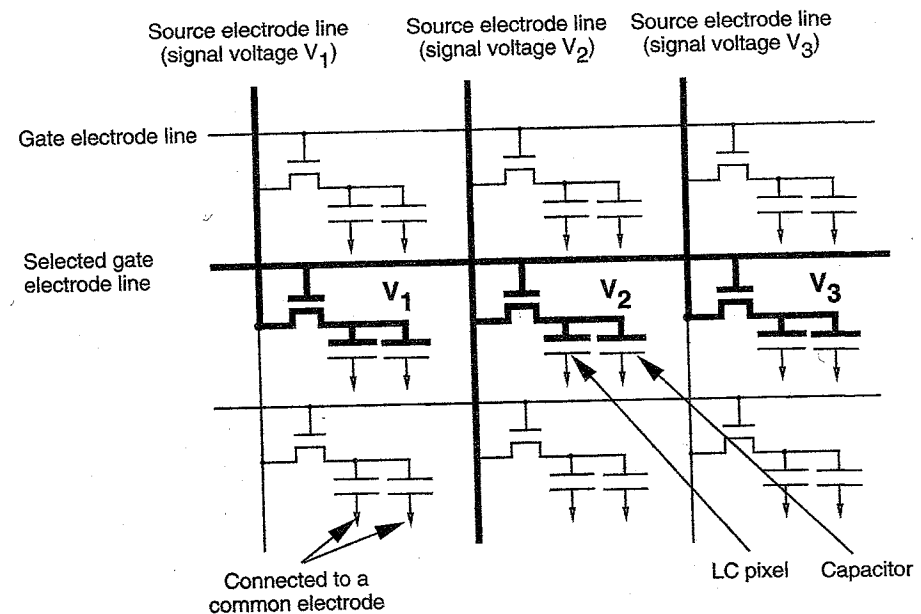


Figure 3.10 Equivalent circuit for a TFT panel

electrode line is scanned and a positive pulse voltage is applied, on this pulse, a signal voltage is applied to all the source electrode lines. If, at the same time, a voltage that can drive liquid crystal is applied to the second source electrode (V_2), and a voltage less than the drive voltage is applied to the other source electrodes, only the liquid crystal that corresponds to the center pixel is activated. If we do not supply a voltage to a gate electrode, it remains open, and therefore, the problem of crosstalk, which can occur in passive matrix devices, does not occur. By scanning the gate electrode lines sequentially according to these operating principles, and by applying voltage pulses to all source electrode lines in a sequence according to the respective pixel drive status, it is possible to address all required pixels. In this manner, one frame of graphical information is displayed, and by repeating this operation moving pictures can be produced.

3.1.4 The TFT Described

Several types of TFTs exist, each designed for a different application, as described in Chapter 2. Among these types of TFTs, the one most widely used is the inverted staggered TFT. The mass production of inverted staggered TFTs that is now possible owes to a large extent to very intensive R&D efforts that have been undertaken by several manufacturers to achieve commercial production.

This section describes in detail the design of the inverted staggered TFT that is used in color TFT LCDs.

Figure 3.11 shows the structure of an inverted staggered a-Si TFT, which has a bottom-gate structure. In the following, we describe the structure of this TFT array on a layer-by-layer basis.

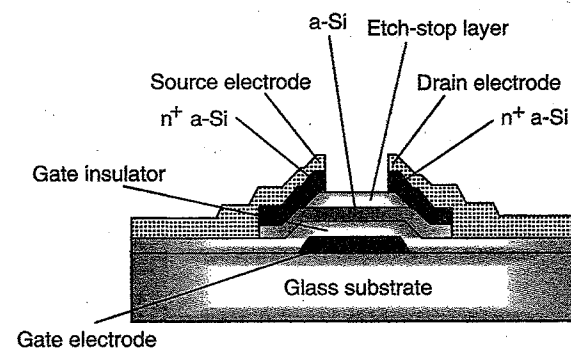


Figure 3.11 Cross-section of a TFT Array

The first layer contains gate electrodes and gate electrode lines (bus lines). Metals such as Cr, Mo-Ta, Ta, and Al are used in gate electrodes and electrode lines. An example is the use of aluminum electrodes. The material from which a gate electrode line is made is closely connected to the formation of the storage capacitor. Figure 3.12 shows a planar diagram of a capacitor. As noted previously, some capacitors are formed by using a part of a gate electrode line, while other capacitors are constructed independent of a gate electrode line. The advantage of using the former type of capacitor is that, using a part of a gate electrode line as a capacitor eliminates the need for modifying the fabrication process or for additional processes. On the other hand, if the gate electrode line is used as a capacitor, there is an increase in the time constant for the gate electrode, which reduces the TFT switching speed. According to calculations, this problem can be solved by using electrodes that are substantially lower in resistance than electrodes made of Cr or Ta. This is the reason that aluminum electrodes are used in certain applications. However, the technique of using aluminum as the gate electrode material

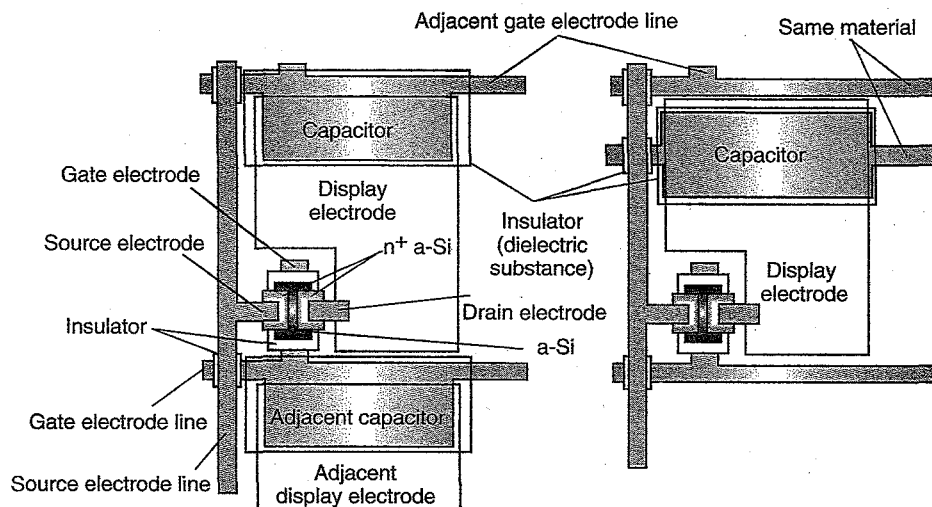


Figure 3.12 Types and structures of capacitors

is still new and largely untested. In actuality, however, a capacitor should be formed independent of the gate electrode line in order to lower the time constant for the gate electrode and to reduce the number of variables that contribute to the instability of the resulting device. Therefore, the thrust of developmental efforts is shifting in favor of using independent capacitors.

Aluminum offers another advantage over other metals: an insulating oxide. On an aluminum electrode, the aluminum oxide (Al_2O_3) layer that is formed by anodic oxidation can serve as an insulator. Compared with the Ta_2O_5 layer on a Ta electrode, the Al_2O_3 layer has a leakage current that is several orders of magnitude lower, which confers an outstanding performance characteristic on the layer. Furthermore, the fact that the aluminum oxide layer possesses an electrode adhesion property equal to that of Cr or Ta insulators has led to the development of Al gate

structures on which an insulator film can be formed simply by anodic oxidation.

Normally, two layers of insulators are formed on a gate electrode. This is because a double-layer structure substantially reduces the occurrence of defects, such as pinholes, which can be a significant problem in the manufacture of single-layer structures. If Al_2O_3 is used as the first layer, SiN_x is used as the second layer. The SiN_x insulator is an especially critical component. It is said that the gate insulator properties have a greater bearing on the performance of the resulting TFT than the a-Si property does. Figure 3.13 shows the relationship between gate voltage V_G and drain current I_D . As illustrated in Figure 3.13, the voltage V_{th} at which the flow of current commences is referred to as a threshold value. The structure constructed in this manner,

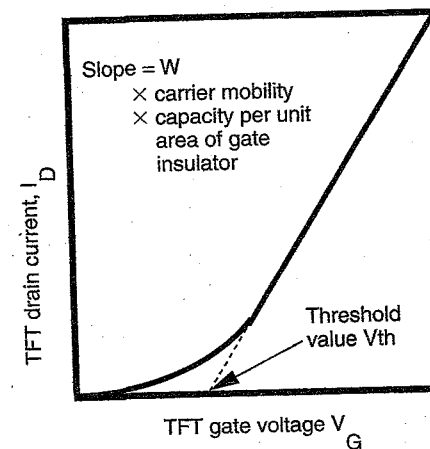


Figure 3.13 Relationship between the gate voltage and the drain current in a TFT

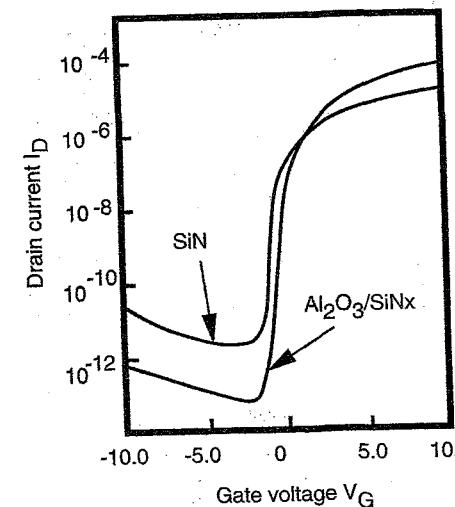


Figure 3.14 TFT properties and different insulators

with an Al gate electrode and double-layer insulators of Al_2O_3 and SiN_x , offers reduced gate-pulse delay due to aluminum's low resistance, while exhibiting an excellent insulation property. Figure 3.14 shows the voltage/current characteristic of this structure, which can produce a higher ON/OFF current ratio compared with a single layer of SiN_x . Although aluminum suffers from the problem of hillocks, the advantages of aluminum seem to outweigh this disadvantage, and aluminum gate processes will gain greater acceptance.

After constructing the gate electrode/insulator structure, the next step is to deposit an a-Si layer. A significant advantage of the a-Si TFT lies in the fact that it only requires a maximum deposition temperature of 300°C in the manufacturing process, which contrasts with the minimum $600\text{--}1000^\circ\text{C}$ temperature required in the p-Si TFT process. When light strikes a-Si, the resulting photoelectric conversion produces a current, thus increasing the amount of off-current. This property, which proves useful in solar cells, can cause malfunction in the case of an LCD. To prevent this problem, the a-Si layer must be completely shielded from light. An inverted staggered device is constructed in a continuous process that forms three layers: insulator (SiN_x), a-Si, and protective layer (SiN_x), over the gate electrode. After that, drain electrodes and source electrodes are formed. The reason that an insulator (SiN_x) is required on the a-Si layer is that, when drain electrodes and source electrodes are formed by sputtering, or when these electrodes are subjected to patterning by means of dry (plasma) etching, the a-Si thin-film needs to be protected from damage. This is the reason that the second SiN_x layer is required.

After opening contact windows in the top insulator (SiN_x), metal source and drain electrodes are formed. However, for low-resistance transfer of electrons, these electrodes cannot be formed directly on the a-Si layer. An n^+ a-Si ohmic layer must be formed between the metal electrodes and the a-Si layer. This improves the contact between the metallic source and drain electrodes and the a-Si ohmic layer. And finally, metallic source and drain electrodes are formed. This completes the construction of the a-Si TFT.

Now that we understand how the stacked structure is formed, we next turn to how various shapes are designed. The inverted staggered structure shown in Figure 3.11 can exhibit a variety of TFT performance characteristics, depending on the thickness and area of layers. A typical example is the thickness of an a-Si layer. As noted before, when light strikes an a-Si film, the resulting photoelectric conversion generates a current. The most effective solution to this problem lies in reducing the thickness of the a-Si layer to approximately 50 nm. As a second approach, in order to shield light, the film is covered with metal electrodes and a black matrix. The larger the light-shielding cover in terms of area, the more effective the light-shielding effect. On the other hand, a reduced aperture lowers the brightness of the display, which affects the very quality of the resulting LCD. To circumvent this problem, simulation studies are conducted with the view toward designing TFT arrays efficiently, in order to increase the aperture as much as possible. At present, the largest aperture that can be attained, even for 10-inch color TFT LCDs, is approximately 70%. The display electrode shown in Figure 3.15, in contrast, has an effective aperture of only 40.7%.

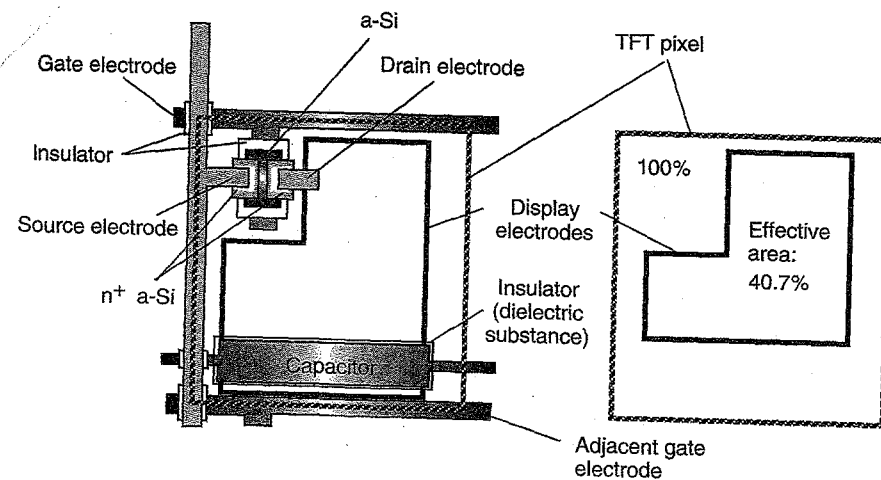


Figure 3.15 Aperture of a pixel

Another important design consideration is the channel. The channel refers to the area on an a-Si film between source and drain electrodes. Figure 3.16 shows a channel structure. The part of the figure that corresponds to "S" indicates the channel length. "L" denotes the design channel length that allows for a ΔL process margin. Ideally, the channel length should be $L=S$. However, for the exposure of the UV-sensitive photoresist as part of a patterning process, an alignment margin ΔL is required. No matter how high the attainable precision of the stepper may be, it

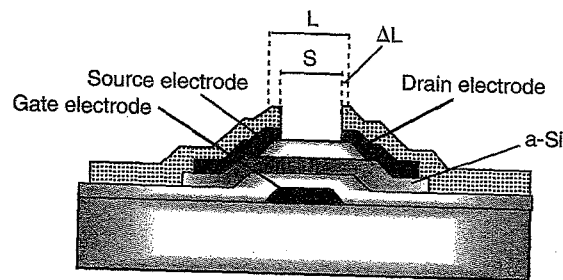


Figure 3.16 Channel structure

is not possible to achieve a complete match between the channel and the electrodes. The difference between channel and electrode spacing accounts for some of the variability in TFT performance characteristics.

A capacitance occurs between source and drain electrodes on one hand and gate electrodes on the other hand because of structural constraints. This capacity is termed parasitic capacitance, which also varies as a function of patterning misalignment. One technique that is employed to prevent this problem involves exposing the photoresist from the back side, using a gate electrode as a mask. This technique is called the self-alignment method.

3.1.5 Design for Redundancy

The occurrence of defects in the TFT fabrication process is virtually unavoidable. Beyond improving production yields in the fabrication processes, one approach to solving the problem is a fail-safe redundant design. The following are some of the redundant designs that have been employed:

- (1) A double-insulator layer structure intended to reduce the number of insulation defects
- (2) Providing multiple TFTs, as shown in Figure 3.17, in order to ensure that even if one TFT fails, other TFTs can provide a backup
- (3) A design in which duplicate bus lines, using two conducting layers, are provided in order to prevent the problem of line breakage
- (4) A repairable design, predicated on the assumption that defects can be repaired

While these techniques are effective for dealing with defects, however, in some cases they can reduce the pixel

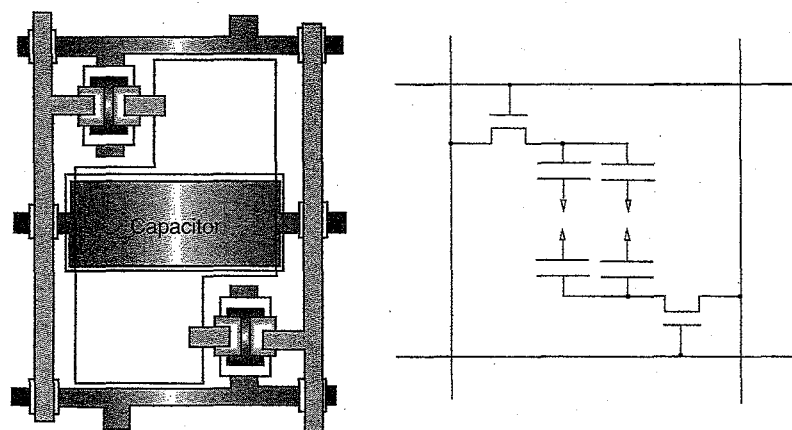


Figure 3.17 Redundant design for a TFT

aperture. Therefore, whether or not a redundant design should be employed must be considered in conjunction with the level of process technology that can be brought to bear.

3.2 MANUFACTURING THE TFT ARRAY

This section discusses the fabrication method for inverted staggered a-Si TFT LCDs in connection with the fabrication equipment that is used.

3.2.1 Photolithographic Process

First, let us focus on the photolithography process, which is a patterning process common to all TFT fabrication processes. Figure 3.18 depicts the photolithography process.

Requisite to the photolithography process is a glass substrate. The substrate that will be turned into an actual product is called a workpiece. On its surface, a workpiece can contain a pre-formed pattern. Organic and inorganic particles that are present on the surface of the substrate are removed by means of brush-cleaning (scrubbing)

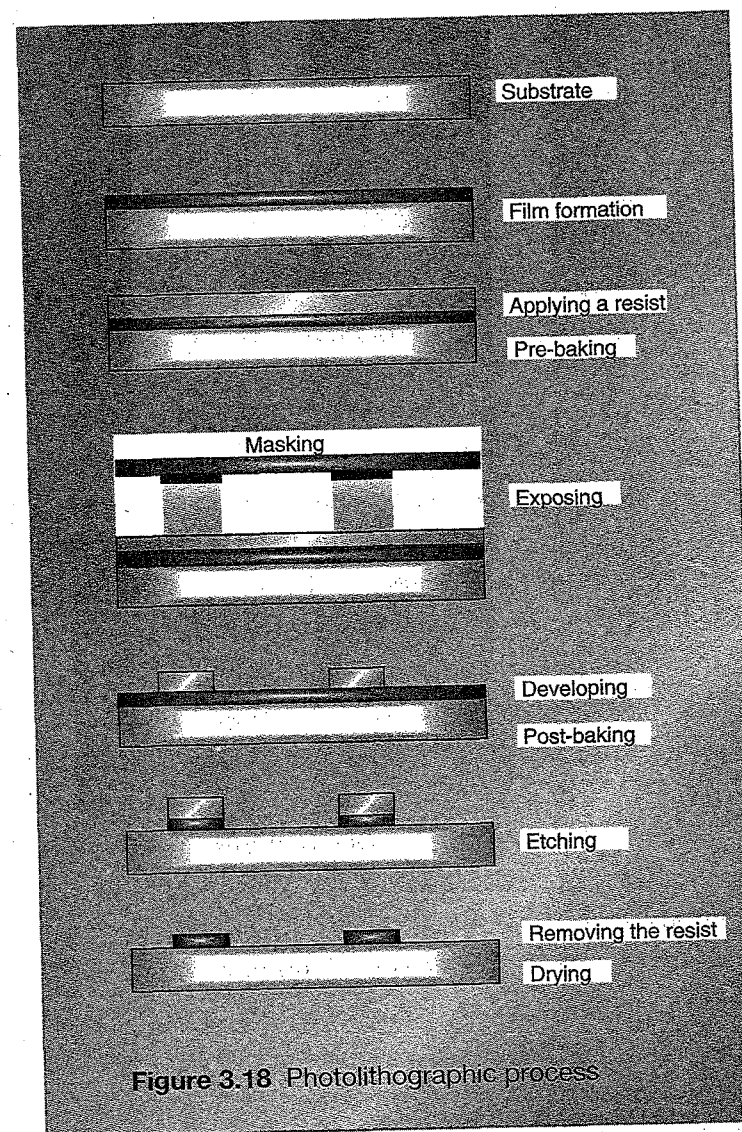


Figure 3.18 Photolithographic process

ultrasonic cleaning, UV-cleaning, pure-water cleaning, isopropyl alcohol (IPA) cleaning, and solvent cleaning in order to render the substrate surface completely particle-free. The success or failure of the cleaning process has a

large bearing on the yields of the products that emerge from the fabrication process.

The intended thin-films are formed on the substrate thus cleaned. Various methods can be employed to form a thin-film, including sputtering, plasma chemical vapor deposition (CVD), and vacuum deposition, depending on the intended application.

Sputtering involves causing accelerated ions to strike the solid surface of a thin-film-forming material, called a target. The ions knock off the material, thus causing the latter to deposit itself on the substrate. There are several variants of the sputtering method: the direct-current sputtering method that forms films of metals, such as Cr and Ta, and oxides; and the high-frequency (10 MHz) sputtering method, in which films of insulator oxides, such as SiO_2 , are formed. Another variety is the reactive sputtering method, in which a film of an alloy is formed and converted into an oxide by an oxidation reaction.

Plasma CVD is used for the deposition of insulators, including a-Si, SiN_x , and SiO_2 . This method produces a film through the use of gas-phase chemical reactions and the plasma that enhances the reactivity of the gases involved.

Vacuum evaporation involves vaporizing a material in a vacuum and allowing the material to deposit onto the substrate. Resistance-heating and electron beams provide the necessary energy for the evaporation process.

After a thin-film is formed, a UV-sensitive resin film called photoresist is coated onto the thin-film that has been formed on the substrate. There are resin monomers, such as acryl-based monomers, that are called negative-resists and that polymerize by the action of light; and novolak-based resins, called positive resists, that break down when

exposed to light. In actual use, the viscosity of the photoresist solution is a critical factor that determines the uniformity of the resulting photoresist film. Therefore, the judicious selection of the solvent to be used is of paramount importance. Several solvents are available: ethyl cellosolve acetate (ECA), methyl isobutyl ether (MIBE), and γ -butyrolactone. Spin coating and roll coating are some of the coating techniques employed.

Spin-coating involves applying a coating of a photoresist solution to a substrate through the use of a dispenser, and spinning the coated substrate in order to ensure that a coating of a uniform film thickness is achieved by means of the centrifugal force applied. The amount of photoresist used is approximately 15 cc/300 mm² of substrate. However, the use of centrifugal force causes over 90 percent of the photoresist to be wasted. This is the price one pays for achieving an excellent film thickness uniformity, with a variability of less than 3% as measured on the surface of the substrate.

Roll-coating involves impregnating grooves, which have been cut into rolls, with a coating liquid and applying the photoresist solution to the substrate in order to form a photoresist film. The roll-coating method is a contact coating method. A drawback is a relatively poor ability to maintain uniformity (for a photoresist thickness variability of less than 10%). On the other hand, it requires only one-third as much photoresist solution as the spin-coating method. Spin-coaters and roll-coaters are available that permit cleaning, coating, exposing, developing, and etching processes on an integrated production line basis.

After photoresist is applied, the substrate undergoes pre-baking, after which it is sent to the exposure step. For

exposure, either g-line (436 nm) or i-line illumination (364 nm) is used. In the exposure process, a mask is used, which is similar in function to a photographic negative film. In actuality, either a quartz or a non-alkaline glass substrate is used, on which patterns are present in a thin-film of chromium.

The exposure equipment is generally referred to as an aligner, due to the fact that exposure involves aligning the target substrate with the mask. In one exposing method, a mirror is used (Figure 3.19), and parallel beams of UV light are directed onto the photoresist film through the mask. This technique is called the proximity method. Another method, the lens-projection method, involves using a lens to form an image on a substrate. In still another technique, the mirror-projection method, an image is formed on a substrate through the use of a mirror.

The proximity method is further divided into a contact method, in which the mask is allowed to come into contact with the substrate; and a proximity method in the strict sense, in which a gap (a proximity gap) is maintained between the mask and the substrate. The contact method is liable to create particles and to damage the mask. Therefore, mass production requires the use of the proximity method, shown in Figure 3.19. In reality, however, even with the use of parallel beams of light, optical interference can produce blurry images. Therefore, the proximity method is used only for producing relatively rough patterns, such as for making color filters. In situations where the need for crisp images requires the use of the contact method, multiple working masks are produced from a master mask, and contact exposure is carried out on these daughter masks. Thus, the proximity method allows

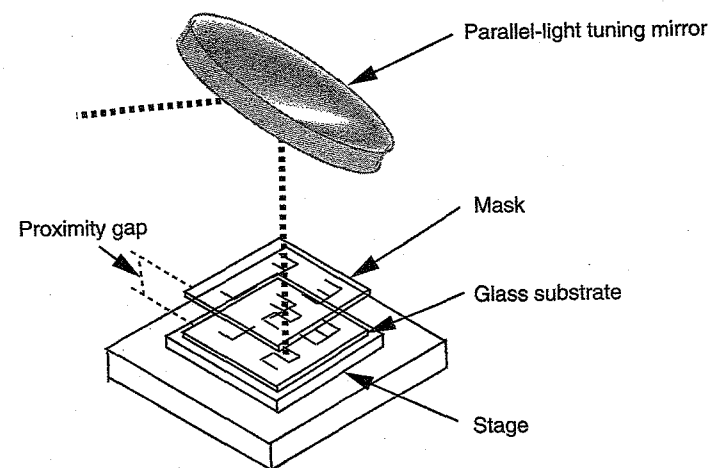


Figure 3.19 Proximity exposure system

one-shot exposures, in which a large image can be produced with an exposure time of 1 to 5 seconds. Therefore, compared to the stepper method (more on this later), the proximity method offers the advantage of permitting significantly faster exposure operations.

The lens-projection method is also referred to as the stepper method, because patterns are exposed by moving substrates stepwise. A stepper performs exposure actions by sequentially changing reticles (small masks). Because a stepper is capable of performing exposure operations in steps, by moving the stage on which a substrate is fixed, the stepper can be a powerful tool in applications where exposure is performed repeatedly on a substrate by using reticles (small masks) of the same design. A case in point would be producing 20 3-inch TFT panels from a substrate measuring 400 mm x 300 mm. On the other hand, exposing a large TFT LCD, such as a 10-inch panel, with a stepper requires splitting one screen into several reticles. This

requires a TFT array design that allows an appreciable amount of mask pattern misalignment (approximately $1\text{ }\mu\text{m}$). Figure 3.20 shows an example in which four reticles are used in the lens-projection method and in which one screen is exposed in four shots instead of one. The stepper is able to change the reticles sequentially.

The mirror-projection method uses the type of equipment shown in Figure 3.21. This system incorporates a stepper mechanism capable of exposing a $400\text{ mm} \times 300\text{ mm}$ substrate in two steps by moving an arc-shaped light beam in a scanning motion. This system can produce two 10-inch TFTs using only one mask.

As indicated above, exposure operations are performed in order to create patterns in the photoresist. To fully utilize the capabilities of an exposure system, the number of particles in the clean room must be controlled rigorously.

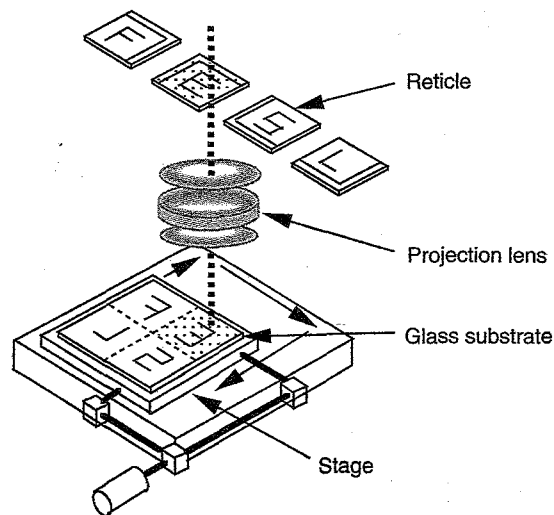


Figure 3.20 Lens-projection exposure system

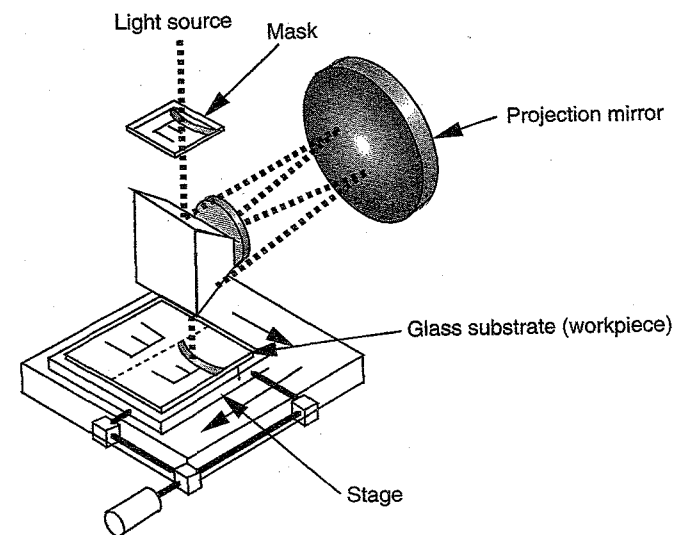


Figure 3.21 Mirror-projection exposure system

In addition, temperature and humidity must also be managed strictly. A one-degree change in temperature, for example, expands or shrinks a $400\text{ mm} \times 300\text{ mm}$ substrate by $1\text{ }\mu\text{m}$. Therefore, equipment maintenance and environmental management is as important as the hardware.

After the exposure process is completed, the next step is the development process. Both TFT array substrates and color filter substrates are developed in an alkaline solution. In most cases, alkaline development involves the use of sodium carbonate and organic alkaline substances (e.g., trimethyl ammonium hydride — TMAH). Because these substances are subject to neutralization by the carbon dioxide gas present in the air, they are formulated as buffer solutions. The developing solution dissolves any unexposed portion of the negative resist and any exposed portion of the positive resist. The extent to which the images on a photoresist are defined sharply depends on a

judicious balance between factors such as the developing temperature, developing time, exposure time, and pre-baking time employed.

As a general rule, a set of conditions is sought that produces a uniform development for the entire substrate within 60 seconds. After the development process, pure water is used to completely rinse out the alkaline constituents. Because the developing solution is inexpensive, a shower developing method is employed for maximum throughput. Because TFT arrays abhor alkaline metal ions, organic alkaline solutions that are free of any alkaline metal ions are used. For developing TFT arrays, a spin development system similar to photoresist coating equipment is used.

In the next step, the etching process, the photoresist forms a protective film on top of the thin film on which patterns are to be formed, and any portions of the thin-film that are not covered by the protective film are removed. There are two etching processes: a chemical dry-etching process, in which gas plasma is used; and a wet-etching process, in which acids and other chemical solutions are used.

In chemical dry-etching, plasma is used to generate gas radicals, such as fluorine radicals, in order to etch the thin-film. The etching process removes any portion of the thin-film that is not covered by photoresist.

In wet-etching, a chemical solution (etchant) is used to etch a thin-film. For etching an ITO electrode, for example, an acid mixture of hydrochloric acid, nitric acid, and ferric chloride is used as an etchant. This etching solution dissolves the portions of the thin-film that are not covered by photoresist. The extent to which patterns can be etched sharply depends on a balance between factors such as etching temperature, etching time, and the concentration

of the acid. Normally, a set of etching conditions is sought that achieves a uniform etching of the entire substrate within 90 seconds. After etching, pure water is used to remove any excess acid.

As the final step, the photoresist that remains on the thin-film pattern is removed. This is done either by plasma (dry)-ashing or wet-removal in a strongly alkaline solution.

Plasma-ashing, as the name implies, involves a plasma to effect removal. In most cases, alkaline removal involves the use of strongly alkaline ions. The liquid can completely remove any residual photoresist (photoresist patterns). Normally, a set of conditions is sought that is capable of effecting removal on the entire substrate within 60 seconds. After that, pure water is used to completely rinse out any remaining alkaline constituents.

In the above patterning operations, the primary focus is on ensuring high product quality while maintaining adequate yields. High throughput and low cost are also important production goals.

3.2.2 TFT Array Structure

Figure 3.22 shows a flowchart for the fabrication of a-Si TFT arrays for making color TFT LCDs. Each of the production steps shown in the figure uses the photolithography process that was described in Section 3.2.1. Normally, non-alkaline glass is used as a glass substrate. Gate electrodes are formed from metals like aluminum or tantalum by sputtering the metal on a glass substrate, and patterning the thin film deposit. Sputtering is used to form gate insulators like Ta_2O_5 , while plasma CVD forms SiO_2 and SiN_x insulators. In some cases, insulators are made in two layers. For example, aluminum electrodes are anodized to

form the first layer (Al_2O_3), followed by sputtering or plasma CVD to form a second insulator layer of Ta_2O_5 , SiO_2 , or SiN_x . The temperature used in this step is the highest temperature for the entire TFT process. After insulators are formed, plasma CVD is used to successively stack an a-Si film and an SiN_x film, which serves as an etch-stop layer. After that, the etch-stop patterns are formed. This is followed by the deposition of a low-resistance n^+ a-Si layer and a third patterning step, in order to construct a-Si islands. Then, film deposition and patterning operations construct the ITO display electrode and drain/source electrodes. This completes the construction of a TFT array.

3.2.3 TFT Panel Structure

Figure 3.23 shows a color TFT LCD fabrication process. First, a thoroughly cleaned TFT array substrate, prepared

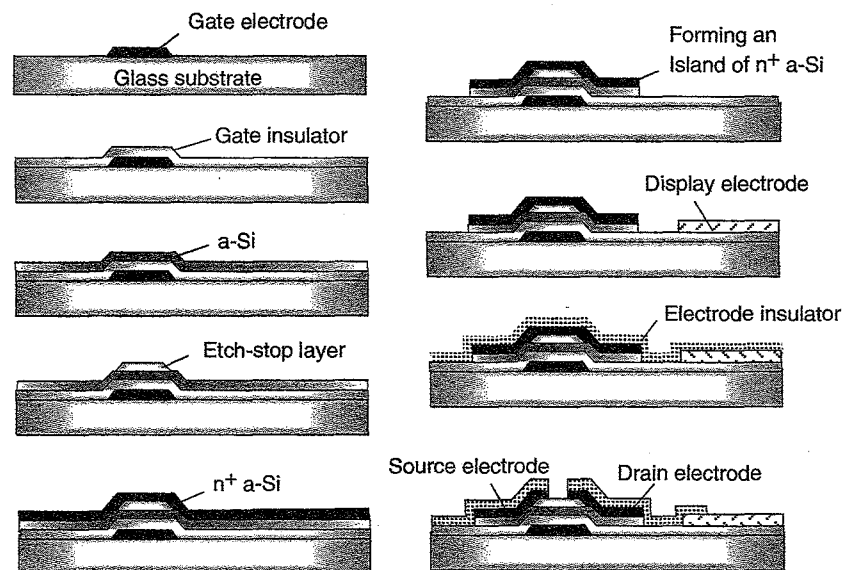


Figure 3.22 TFT array fabrication process

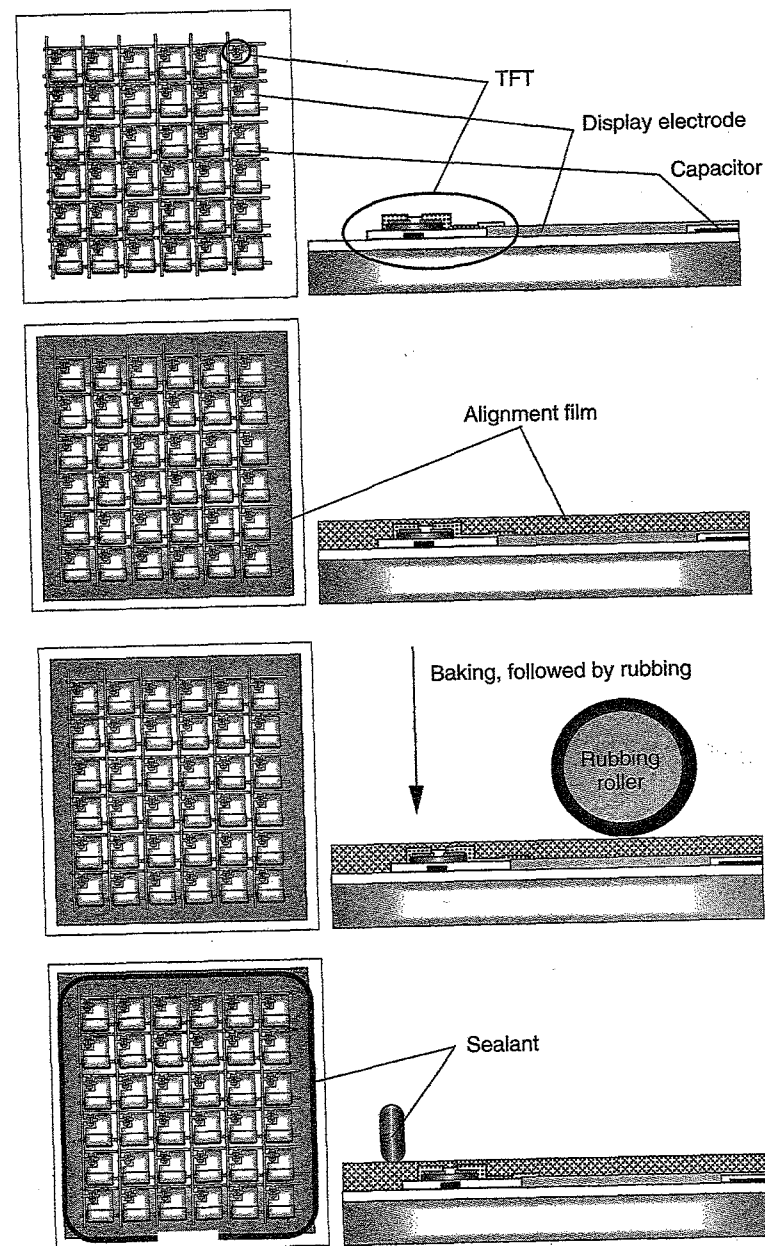


Figure 3.23 Panel process (rubbing)

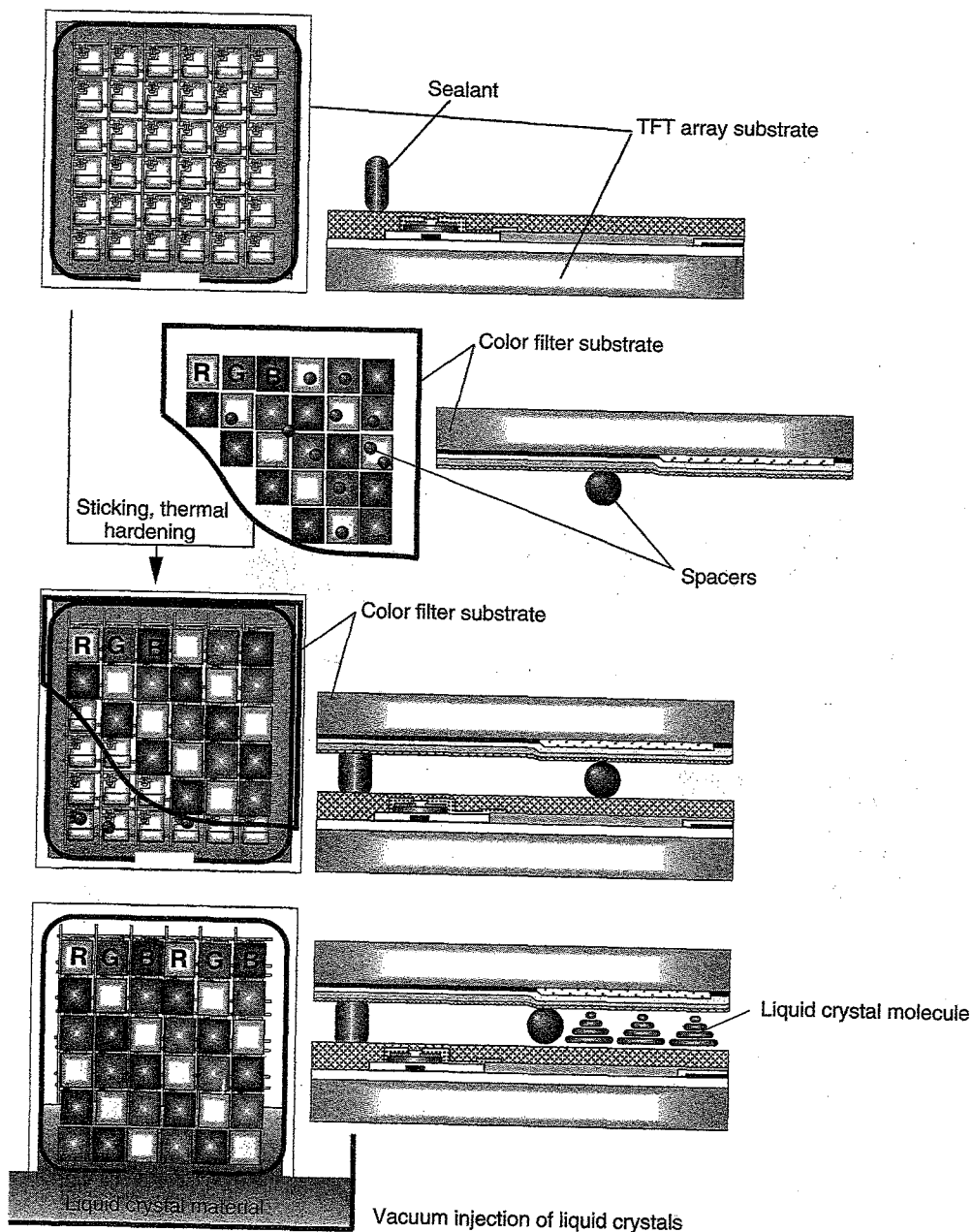


Figure 3.23 Panel assembly process (continued)

according to the procedures described above, is coated with a polyimide alignment film by printing. The target film thickness is 500 Å to 1000 Å (0.1 μm). The applied alignment film is baked at 180°C. Then, a piece of cloth wound on a roller is used to rub the film in order to orient the polyimide molecules in one direction. Although the mechanical friction caused by the rubbing operation does not damage the TFT, the resulting static electricity can. Therefore, the surrounding gate electrodes and source electrodes are shorted in order to prevent damage by static electricity. Similarly, alignment films are formed on color filter substrates, and these substrates are also rubbed.

After the aligning process, a sealant containing spacers is applied. Similar to the cell gap-control spacer, the spacers that are mixed in the sealant have either spherical or needle-like constituents. Also, to facilitate the connection of lines from the common electrodes on the color filter substrate to the TFT array substrate, the TFT array substrate is coated with an electrically conducting paste when the sealant is applied.

As the next step, the sealant and the paste on the TFT array substrate are pre-hardened. At the same time, an appropriate amount of cell gap-controlling spacers are sprayed onto the color filter substrate. The amount to be sprayed is two to three spacers per pixel. In some cases, spacers are sprayed onto the TFT array substrate, and a sealant is applied to the color filter substrate. In either case, the TFT array substrate and the color filter substrate are stitched after the pre-hardening of the sealant and the spraying of the spacers. After that, the sealant is hardened completely. The resulting structure is an empty cell. After the stitching is complete, the cell is filled with liquid crys-

tal material by vacuum injection. Finally, a sealing agent is used to seal the liquid crystal cell. This completes an LCD panel. When a TAB (more on this later) is connected to the LCD panel and polarizers are attached, the result is a complete LCD module.

3.3 ADDRESSING THE TFT ARRAY AND DRIVER LSI

3.3.1 TAB LSI

Driving a TFT requires driver LSI circuits. A chip-on-glass (COG) method has been developed that mounts driver LSI's directly on the TFT substrate. However, because in this method a bad LSI chip renders the entire substrate, including the TFT, defective, a tape-automated bonding (TAB) method is normally employed to first attach a driver LSI to a tape carrier package (TCP), and then to connect the driver LSI to the TFT array substrate through the TCP.

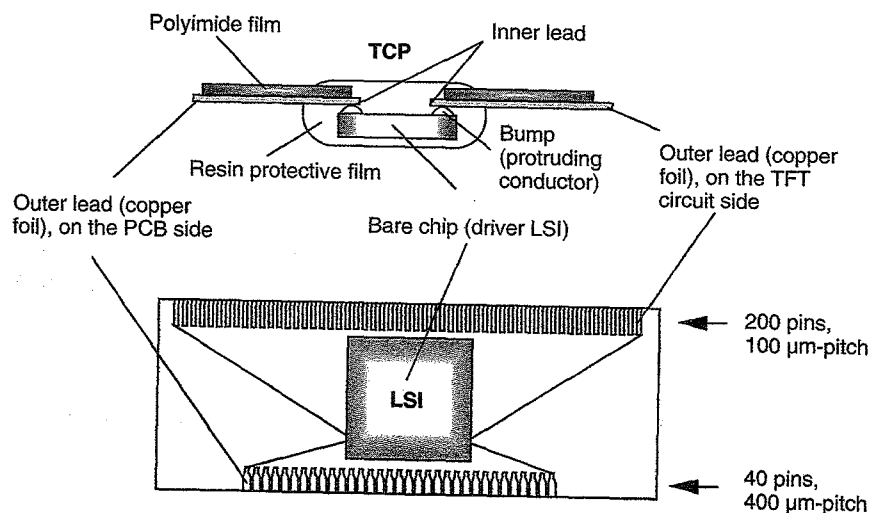


Figure 3.24 Structure of the TCP used in the TAB method

This method has gained wide acceptance. Figure 3.24 shows the structure of a TCP. The TCP process begins with attaching leads to an LSI chip called a bare chip. The lead oriented toward the TFT panel or the printed circuit board is called an outer lead, and that oriented toward the LSI side is called an inner lead. A lead has a structure in which a stripe-shaped copper foil electrode is attached to a polyimide film. To connect the inner lead to the bare chip, protruding features called "bumps" must be formed on the LSI chip. The LSI chip is attached by pressing the bumps onto the inner leads. Finally, a resin protective film is formed. This completes the fabrication of the component called the TCP. The TAB method refers to the process of producing TCPs.

Figure 3.25 shows the manner in which circuits are connected to the LCD conducting lines with a TCP. Circuits are connected to the TFT array substrate side using an anisotropic conducting film (ACF). As shown in Figure 3.26, this film contains particles of an electrically conducting substance that are dispersed in a heat-hardening resin film. When subjected to pressure-bonding, only the electrically conducting parts of the film become connected. The

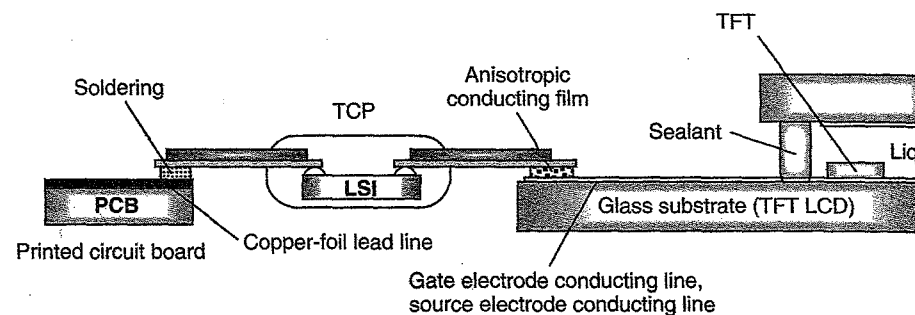


Figure 3.25 Mounting a TAB

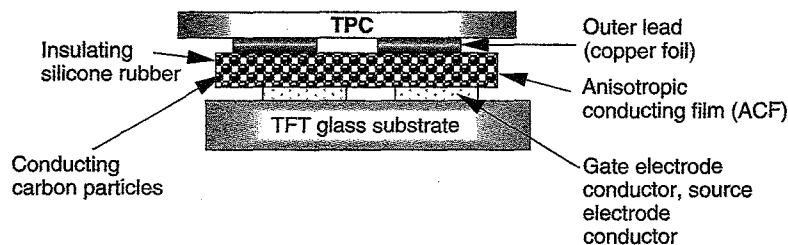


Figure 3.26 Connecting a TPC to a TFT array substrate using an ACF

ACF permits the interconnection of stripe-shaped conductors of 100- μm pitch. For connecting circuits to an opposite printed circuit board, soldering is employed. At present, the minimum pitch that can be attained by soldering is approximately 400 μm .

3.3.2 Addressing the TFT Array

Figure 3.27 shows the equivalent circuit for a pixel in a TFT LCD. In the figure, the parasitic capacitance C_{gd} between gate and drain, and the parasitic capacitance C_{ds} between drain and source, as well as that between the source electrode and the display electrode, are indicated by dotted lines. The equivalent circuit represents one pixel in the TFT LCD array that is shown in Figure 3.10. In what follows, we discuss how a pixel—i.e., the liquid crystal layer between the display electrode for one pixel on the TFT substrate and the common electrode on the color filter substrate—is addressed.

A liquid crystal layer and a capacitor are connected as a load on the TFT. Applying a positive pulse (Figure 3.28) to a gate electrode through a gate electrode line turns the TFT on. This causes the signal voltage applied to the source electrode to be transmitted from the source through the drain to the liquid crystal layer and the capacitor, which

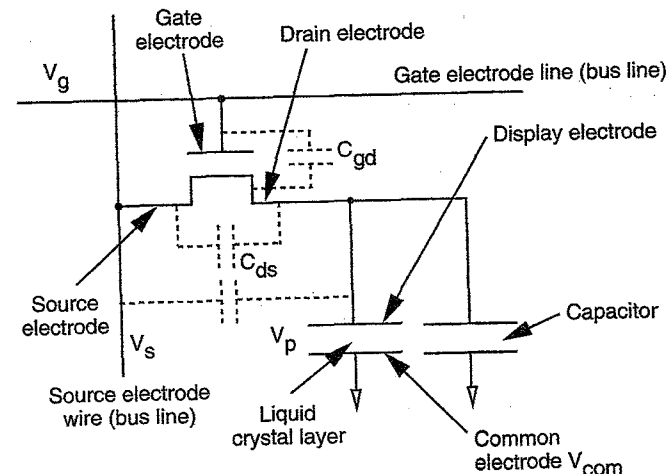


Figure 3.27 Equivalent circuit for a pixel

are a load on the TFT. In this operation, the voltage (display electrode voltage) rises with the gate pulse, and the voltage level at which the gate voltage becomes 0 is maintained and applied to the liquid crystal. In strict terms, however, the voltage undergoes a level shift of ΔV due to the influence of the parasitic capacitance C_{gd} between gate and drain, and changes as a function of the current that flows through the liquid crystal and as a function of the TFT's off-current. This is shown in Figures 3.28 and 3.29. While the voltage is changing in this manner, the pixel receives another gate pulse, as shown in Figure 3.28. Until another signal voltage is supplied, the pixel electrode drives the liquid crystal for 15-20 ms, a length of time which is three orders of magnitude longer than the length of time required to write a signal voltage (20-30 μs for an office automation display). The main function of the capacitor is to maintain the voltage on the pixel electrode until the next signal voltage is written.

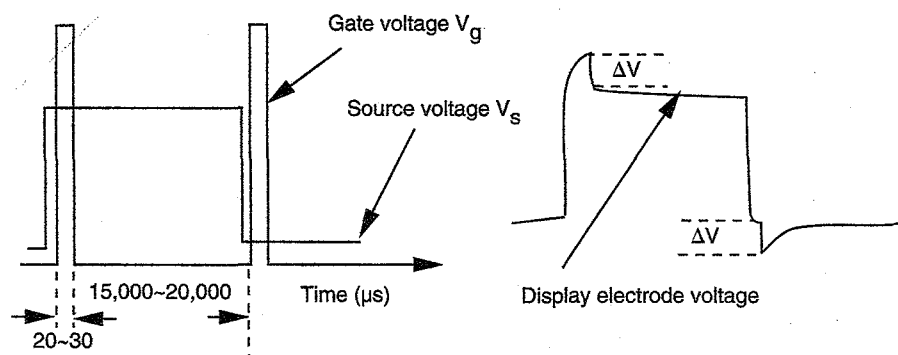


Figure 3.28 TFT drive method

Liquid crystals must be driven by alternating current. Therefore, a TFT LCD is normally driven by a frame-reversal drive method, shown in Figure 3.29. A "frame" refers to the time period in which all gate electrodes are scanned sequentially from top to bottom until the entire screen is displayed. Normally, one frame is 1/60 of a second. When a given voltage level is applied to the liquid crystal successively, the source voltage varies between the first and second frames, as shown in the figure. The display electrode voltage also varies between frames. However, because the voltage applied to a liquid crystal layer is equal to the difference between the display electrode voltage and the common electrode voltage, in the first frame the current flows from the display electrode to the common electrode, and in the second frame it flows in the opposite direction. Thus, the liquid crystal layer is driven by alternating current. It should be noted that the liquid crystal responds to the rms value of a voltage, and the liquid crystal's transmittance changes accordingly. The common electrode voltage is set so that the effective value of the voltage applied to the liquid crystal layer is the same between the first and second

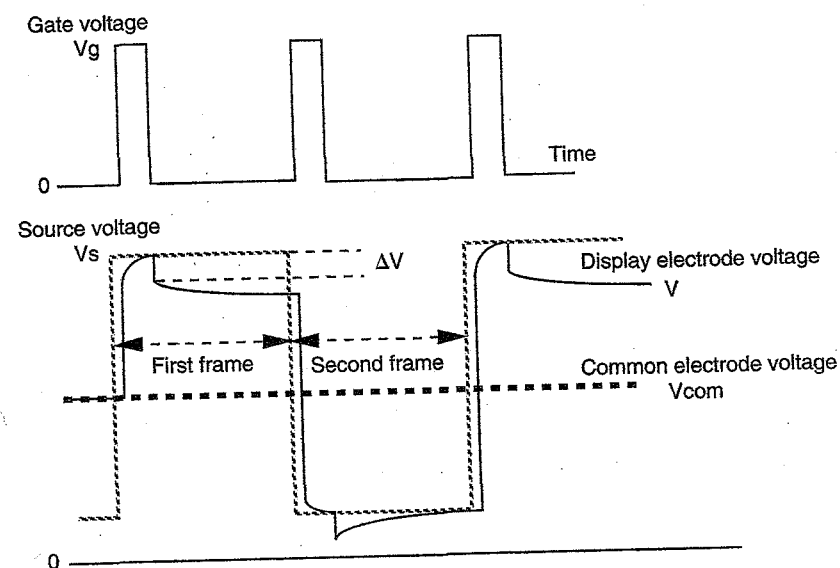


Figure 3.29 Frame-reversal drive method

frames. If the voltage changes between frames, the result would be a 30-Hz flicker. Capacitors are used for preventing flicker and for ensuring consistent displays.

The frame-reversal drive method described above includes variants: an H-line reversal drive method and a V-line reversal drive method. In the H-line reversal drive method, the level of the signal voltage applied to the source electrodes for each gate electrode line is varied in the same manner as a frame reversal. Similarly, in the V-line reversal drive method, the level of the signal voltage applied to the source electrodes is changed alternately on a line-by-line basis. These variations are designed to prevent flicker and to improve the consistency of display. In another variation, intended to reduce the voltage level required, the common electrode voltage is shifted simultaneously with an H-line reversal, and the power supply voltage is shifted.

3.3.3 Displaying Shades of Gray

Gray shade displays are necessary in order to display images that contain halftones, such as photographs, and to produce color images from the three primary colors of RGB. A gray shade display refers to displaying images by providing many intermediate brightness levels between the brightest white and the darkest black. Gray shades can be either discrete numbers of shades, such as 8, 16, 64, or 256 levels of gray, or continuous gray levels. Two basic methods for displaying gray levels exist: a voltage amplitude modulation method (voltage gray-shades method) and a frame-rate-controlling gray-scale method (frame rate gray-shades method). These methods are discussed in detail in this section.

(1) Voltage gray-shades method

The voltage gray-shades method is widely used for gray-shade displays on TFT LCDs. As shown in Figure 3.30, the optical transmittance of a liquid crystal changes continuously as a function of applied voltage (the figure also shows discrete voltage levels for an 8-gray-shade display). As shown in the Figure, the voltage applied to the liquid crystal can be varied by changing for each pixel the amplitude of the signal voltage applied to the source electrode. In this way, many brightness levels can be displayed. The LSI drivers designed to impart the necessary signals include analog drivers, which are capable of producing a signal voltage by changing its amplitude continuously within a specified amplitude range; and digital drivers, which produce discrete voltage amplitudes (amplitudes 8, 16, ..., 256, etc., as mentioned above).

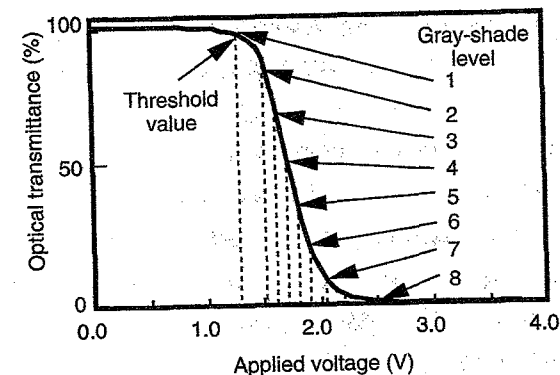


Figure 3.30 Voltage gray-shades method for a color TFT LCD

The analog method is used in small TV sets and other devices that require a relatively small number of pixels, such as a 240x320 pixel display. For high-definition LCDs containing large numbers of pixels, a wide frequency band that is required for display presents a problem in producing an LSI that is capable of modulating the amplitude of signal voltages at the required speed and is small enough to fit in the TFT panel. Although high-definition, large-screen analog units have been developed, most drivers are digital units with limited numbers of output levels, such as 3 bits (8 gray-shade levels, Figure 3.30), 4 bits (16 gray-shade levels), 6 bits (64 gray-shade levels), and 8 bits (256 gray-shade levels).

(2) Frame rate gray-shades method

As mentioned in paragraph (1), efforts to produce many shades of gray using a digital driver LSI must overcome technical hurdles such as the need for a high clock frequency (e.g., 30 MHz for a million-pixel color display) and an attendant increase in LSI chip size. The frame rate

gray-shades method uses a digital driver of a given number of bits in combination with the frame-rate control method in order to achieve an increase in the number of gray-shade levels by one or more bits.

For simplicity, Figure 3.31 shows an example in which the gray-shade level is increased by two using a 1-bit driver for binary display (black and white). In this case, a screen is composed of three frames. Each frame can produce only two brightness levels: the black level produced by signal voltage V_1 , and the white level produced by signal voltage V_0 . In the darkest combination, all three frames are turned black. In the second darkest combination, two frames are turned black. In the third darkest combination,

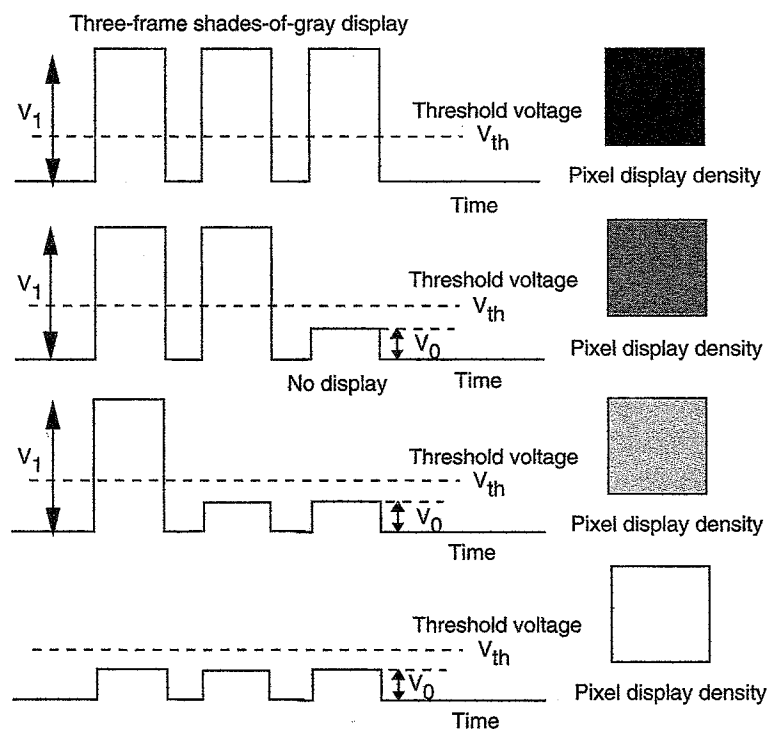


Figure 3.31 Shades-of-gray display using the frame-rate control method

one frame is turned black. And in the brightest combination, all three frames are turned white. In this manner, four shades of gray can be recognized by the human eye as a composite image of three frames. In this case, the display period for one frame should be set at one-third the normal cycle, or 1/180 second, in order to prevent any flicker. Furthermore, the sequence in which black and white displays are produced on the frames is optimized according to the display status of surrounding pixels in order to reduce screen flicker.

The frame rate gray-shades method has been implemented in actual production displays. These models use 3-bit, 8-gray-shade drivers, so that a screen composed of two frames can produce 16 shades of gray.

3.4 THE GLASS SUBSTRATE

3.4.1 Merits of Glass

Virtually all LCD substrates are made of glass. At present, glass is the only substance that can be fashioned in 300 mm x 400 mm dimensions, as a flat, transparent substrate of a 1.1 mm thickness, capable of withstanding up to 350°C of heat, resistant to the effects of acids and alkalines, and, moreover, amenable to mass production. As shown in Table 3.1, although plastic may be acceptable in terms of flatness and transparency, it falls short in heat tolerance. Only glass seems to be able to satisfy all these performance requirements. Although plastic substrates have come into use in passive-matrix LCDs, most substrates for LCDs are made of glass. In the field of TFT substrates, glass is the only substance that is used for making substrates in any appreciable quantities.

Table 3.1 Comparison of substrate attributes

SUBSTRATE	SILICON	PLASTIC	GLASS	CERAMICS
Size: 400 x 300 mm	△	☆	☆	○
Transparency	×	☆	☆	△
Heat resistance, 350°C	☆	×	☆	☆
Chemical resistance, mass-production cost	×	☆	☆	△
△: very good performance ○: poor performance ☆: good performance ×: inferior performance				

3.4.2 Liquid Crystal Display Glass

The glass substrate is a critical component of a color TFT LCD. In contrast to glass plates, such as window panels, that are used as a construction material, the glass that is used in an LCD must be free of warping and surface scratches; moreover, it must be highly stable with respect to heat, and must be free of alkaline constituents. The performance characteristics required of the glass substrate are comparable to those required of the silicon substrate used in the semiconductor industry. A color TFT LCD is made by forming TFT devices and color filters on glass substrates and by joining the substrates. Mounting driver LSI chips and backlight units completes the fabrication of a color LCD. The quality of the glass substrate has a large bearing on the products that emerge from the color TFT fabrication process. As shown in Figure 3.32, the quality of the glass substrate is fundamental to how well thin-films can be stacked in sequence on the substrate. Therefore, the importance of the glass substrate cannot be overemphasized. In the fabrication of TFT arrays, the flatness of the

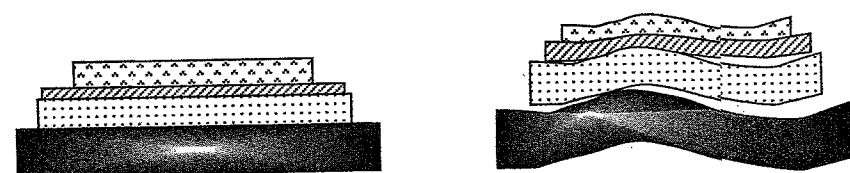


FIGURE 3.32 Thin-films stacked on a flat substrate and those stacked on a substrate containing surface irregularities

glass substrate and the absence of scratches have a significant impact on the resulting production yield.

3.4.3 Manufacturing Glass Substrate

Several methods for producing glass substrates exist: the float method, the redrawing method, the downdrawing method, and the fusion method (Figure 3.33). These methods have all been developed for the mass production of construction-grade glass plates. Incorporating further innovations, the downdrawing and fusion methods have achieved mass production of alkali-free glass (white glass) for use in LCD panels. Incidentally, green glass contains the same constituents as ordinary window glass; its name derives from the fact that the cross-section of the glass appears green. For color TFT displays, alkali-free glass is

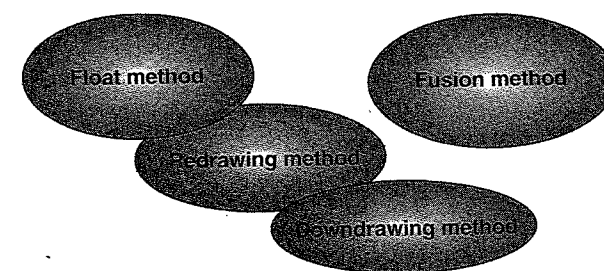


Figure 3.33 Glass fabrication methods

essential. Most of these glass substrates are made in a 1.1-mm thickness, though some displays use 0.7 mm substrates. The float, downdrawing, and fusion methods are all capable of molding and fabricating glass plates of the aforementioned constituents and thickness in a continuous process. The following is a brief description of these three fabrication methods:

The float method is essentially the same as the method for the fabrication of construction-material glass plates (window glass). As illustrated in Figure 3.34, this method involves letting molten glass, under a reducing atmosphere, flow into a refractory vessel that is filled with metallic tin. The flat surface of molten tin permits the molding of flat glass in large quantities. (The glass floats on the surface of tin, hence the name "float method.") In some cases, the glass is not immediately molded into a 1.1-mm thickness. Instead, the floating method is used in tandem with a process called redrawing, Figures 3.35, in which the molded glass (mother glass) is reheated, redrawn, and fashioned into the desired thickness. In either method, the resulting glass exhibits a warped surface and contains contaminants from the molten tin. To eliminate these prob-

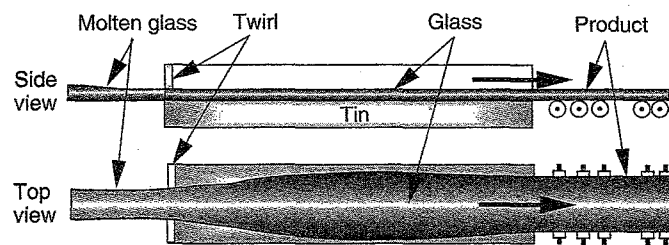


Figure 3.34 Conceptual diagram of the float method

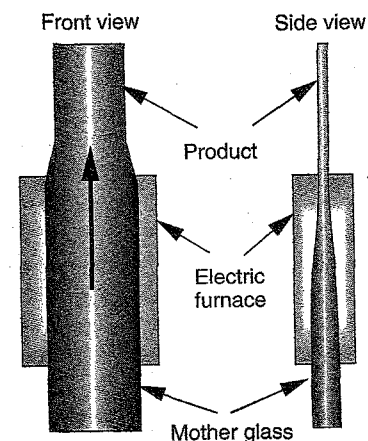


Figure 3.35 Conceptual diagram of the redrawing method

lems, normally the plate is polished on both sides. Because of its low cost, the float method is used in the production of green glass, for which some contamination can be tolerated. In terms of price, whereas where green glass costs only 900 yen (\$10.60 @ 85 yen/dollar) per 300 mm², white glass costs 2000-3000 yen (\$23.50 - \$35.30). Because of the

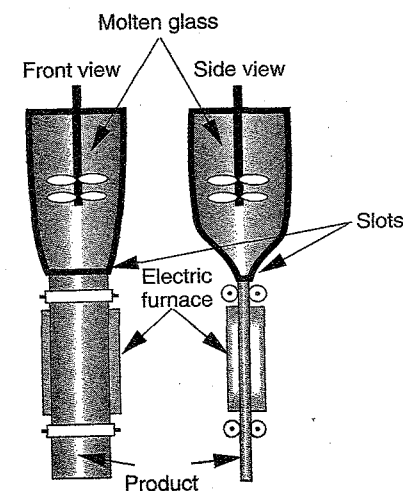


Figure 3.36 Conceptual diagram of the downdrawing method

price differential, these types of glass are used for different applications.

The downdrawing method, Figure 3.36, which is also called the slot-drawing method, involves drawing molten glass downward from a slot with a specified stretching force. By changing slots, glass plates of different thicknesses can be molded continuously. The downdrawing method is well-suited for the molding of thin plates, typically measuring 1.1 mm or even 0.5 mm. Because the resulting glass surface contains minute surface irregularities and scratches that are transferred from the slot, the resulting glass plates are polished, before they are shipped, either on one side or on both sides.

The fusion method is a variant of downdrawing, except that it does not use a slot. As shown in Figure 3.37, this method involves letting molten glass flow into a trough-shaped refractory structure, then allowing it to overflow from the right and left sides of the trough, joining into a single sheet as the glass flows down. Unlike the

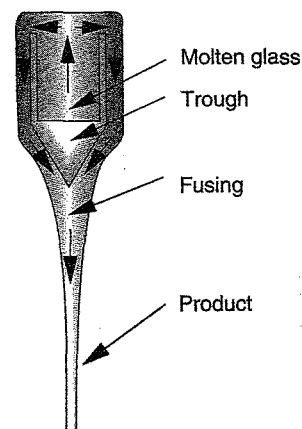


Figure 3.37 Conceptual diagram of the fusion method

other fabrication methods, this method does not cause damage to the surface of the glass due to physical contact, and thus is capable of producing an excellent surface quality. Most of the white glass that is produced commercially is made by the fusion method.

Increasingly, quality control in the production of glass substrate is performed on a lot-by-lot basis. Glass plates that contain many scratches, which occur either at the beginning or toward the end of a production run, are sorted out during the inspection process and sent to a polishing operation; these are used as TFT array substrates. The remaining scratch-free good products are used as color filter substrates. This production control method has significantly contributed to cost reductions.

3.4.4 Alkali-Free Glass for TFT Displays

As explained in Chapter 2, there are two major categories of LCDs: passive matrix displays, such as STN LCDs; and active matrix displays, such as TFT LCDs. Initially, both types of displays were produced using alkali-free glass in order to avoid the adverse impact of alkali ions. Subsequently, it was found that the elution of alkali ions from glass could be prevented through the use of a silica-based film. Ensuing mass production has permitted using low-cost soda-lime glass for glass substrates for passive matrix LCDs.

On the other hand, for active matrix LCDs, the elution of alkali ions from glass has a potentially significant impact on the TFT's performance. Also, for the formation of TFT devices the thermal expansion and contraction of glass must be minimized. Further, the glass must be sufficiently tolerant to the effects of acids and alkali that are

used in patterning operations. Therefore, for active matrix LCDs, alkali-free glass is used because of its superior chemical resistance and tolerance to heat. Some color TFT LCDs employ amorphous silicon, while others use polycrystalline silicon. For glass substrate for a TFT array incorporating polycrystalline silicon semiconductors, glass and quartz glass of high heat resistance are used.

3.4.5 Glass Physical Parameters

Figure 3.38 shows the typical shape of a glass substrate. On the surface, the glass substrate may appear to be an ordinary rectangular glass plate. However, it is on this glass substrate that TFT arrays are formed and color filters are constructed. Further, the assembly process involves attaching the TFT array substrate to a color filter substrate. Therefore, the quality of the glass substrate significantly affects the throughput and yield with which color TFT LCDs can be produced.

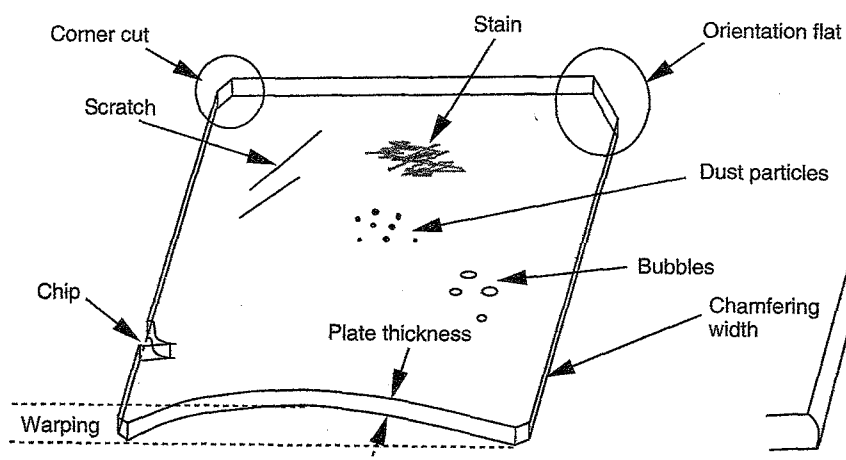


Figure 3.38 Physical parameters of a glass substrate

Typically, a glass substrate is a rectangular plate measuring 300-370 mm by 400-470 mm. Each corner is ground at 45° in a shape called a corner cut. When the top and bottom sides of a glass substrate are to be distinguished, an orientation flat (also referred to as an orientation cut), different from the corner cut, is created at each corner of the substrate. The edges of glass substrate are chamfered in a C- or R-shaped pattern in order to prevent chipping and to inhibit the generation of particles in the fabrication process.

3.4.6 Glass Properties

The properties required of the glass substrate are defined in great detail. These properties are divided into those which are intrinsic to the glass (optical, thermal, mechanical, and chemical properties), and those which concern the shape of the glass substrate (external dimensions, thickness, squareness, straightness, and the absence of warping), surface quality (stains and scratches, surface irregularities, and

TABLE 3.2 Comparison of the properties of glass substrates

GLASS TYPE	GREEN GLASS	WHITE GLASS	QUARTZ	
GRADE	SODALIME	BORO-SILICATE	ALKALI-FREE	
Comp. (%)SiO ₂	72.5	72.0	49.0	99.9
Al ₂ O ₃	2.0	5.0	11.0	—
B ₂ O ₃	—	9.0	15.0	—
Metal (Fe, etc.)	12.0	7.0	25.0	—
Alkali	13.5	7.0	—	—
Coefficient of thermal expansion (/°C)	8x10 ⁻⁶	5x10 ⁻⁶	5x10 ⁻⁶	0.5 x10 ⁻⁶
Softening point (°C)	510	540	590	1070

dust particles), and interior quality (bubbles and foreign objects). Table 3.2 shows typical glass substrate properties. Table 3.3 presents specifications for glass substrates.

3.5 INDIUM TIN OXIDE (ITO) LAYER

3.5.1 Nature of the ITO Layer

The compound indium tin oxide (ITO) is a transparent conducting film. It is made by doping indium oxide with 1-5% by weight of tin oxide. Other transparent conducting films exist, such as tin oxide. However, ITO is most widely used in LCDs because of high conductivity, clarity, and ease of working with the film (patterning by etching).

Of the characteristics of ITO, the clarity is measured using optical transmittance as an index. Most ITO films have an optical transmittance of 80-90% in the visible light

TABLE 3.3 Typical physical-shape specification for a glass substrate

External dimensions	(mm)	$300 \pm 0.2 \times 400 \pm 0.2$ $360 \pm 0.2 \times 465 \pm 0.3$
Thickness	(mm)	1.1 ± 0.1 or 0.7 ± 0.05
Thickness tolerance	(mm)	0.05/400 maximum
Warp	(mm)	0.50/400 maximum
Chamfering	(mm)	0.1-0.6, based on an R chamfering width
Corner cut	(mm)	C 1.5 $\Phi \pm 1.0$ mm
Orientation flat	(mm)	$2.0 \pm 1.0 \times 5.0 \pm 1.5$ or C 4.0 mm ± 1.0 mm
Surface quality		No defects when inspected under 10,000 lux light
Internal quality		No bubbles greater than 0.1 mm in diameter
Edge quality		No chips greater than 0.5 mm

region, which compares well with the transmittance of glass, which is 90-92%. When an ITO film is formed on the entire surface of glass (non-patterned state), it is referred to as a blank ITO film. At first glance, this substrate is highly transparent, and appears as if it was an untreated glass substrate devoid of any film. However, to the trained eye the ITO film's resistance and thickness can be determined by inspection in terms of reflectivity and color.

In terms of conductivity, substances can be divided into three categories: conductors, insulators, and semiconductors. As a general rule, the magnitude of resistance of a substance varies proportionally with the length of the substance, and is inversely proportional to its cross-sectional area. Therefore, the resistance of a sample substance with a length of 1 cm and a cross-sectional area of 1 cm² is called the specific resistance (Ω -cm) of the substance. This value is determined as the resistance specific to that substance. As a rule of thumb, conductors such as metals have a specific resistance of 10^{-6} - 10^{-3} Ω -cm; insulators, 10^6 - 10^{18} Ω -cm; and semiconductors in between. The ITO film has a specific resistance of approximately 10^{-4} Ω -cm, which qualifies ITO as a semiconductor according to this classification. We now turn to the question of what confers conductivity on ITO.

For a substrate to exhibit conductivity, it must satisfy the two factors shown in Figure 3.39. First, it must possess carriers of electricity, and second, it must provide an environment in which the carriers can move around (high mobility). In the case of ITO, it is doped with tin in order to create a medium in which electricity can be transported. An element, such as tin, which is added in trace amounts, is called a dopant. Indium has an atomic valence of +3, and

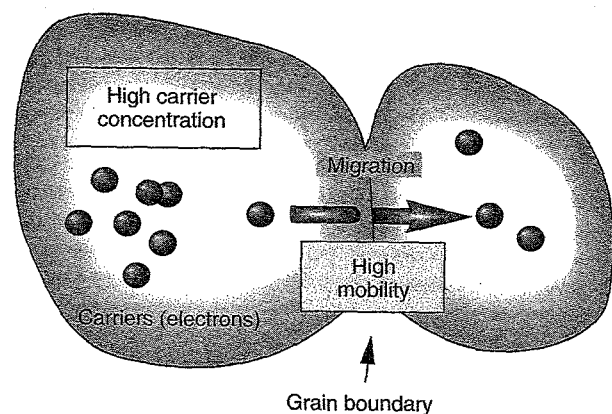


Figure 3.39 Mechanism of electrical conduction in ITO

tin +2. In an indium oxide crystal, oxygen has an atomic valence of -2. Therefore, indium oxide can be expressed by the chemical formula In_2O_3 . By replacing one of the indium atoms by a tin atom, we obtain the compound InSnO_3 . The sum of the valence values of indium and tin is +7, which does not balance with the sum of the valence values of oxygen, which is -6. Therefore, the one excess electron from the oxygen atom becomes free, and it is this electron that confers a conductivity, similar to the conductivity of a metal, on ITO. The free electron is called a carrier. The concentration of carriers can be varied by the amount of dopant that is added. It does not follow, however, that the higher the concentration of tin the higher the concentration of carriers. There is a concentration range in which the carrier concentration is optimized. Research indicates that a dopant concentration of 1-5% by weight is the optimal level. Further, for controlling the carrier concentration, it is important to add trace amounts of oxygen during

sputtering in order to regulate the atomic valence of indium. Regulating the conductivity of the resulting film requires delicate control of the amounts of dopant and oxygen that are added.

Another factor that governs conductivity is the environment in which carriers can move around. To increase the carrier mobility, the speed of carrier migration within the ITO particles should be increased and the grain boundary resistance between particles that compose ITO should be reduced. To this end, the crystal formation of ITO must be promoted, and the carrier migration resistance on the grain boundaries must be reduced. An effective way to promote the crystallization is to increase the substrate temperature. However, an excessively high temperature or an inadequate partial pressure of oxygen can produce a coloration. Therefore, the oxygen concentration should be held at about 3%. Low-resistance ITO with a sheet resistance of $10 \Omega/\square$ is formed at 250°C , and high-resistance ITO with a sheet resistance of $100 \Omega/\square$ is formed anywhere between room temperature and 180°C . An effective way to reduce the grain-boundary resistance is to increase the crystal grains of ITO in order to reduce the grain boundary area. On the other hand, too large a crystal grain leads to surface roughness and can cause the reflection and scattering of light. Therefore, an optimum grain size should be achieved by adjusting the sputtering speed.

Thus, producing a conducting film in a reliable manner requires a delicate control of the amount of tin to be added to achieve a carrier concentration of $10^{20} - 10^{21}$ atoms/cc, and the judicious regulation of the crystallization and the oxidation state of the film in order to increase the electron mobility.

3.5.2 ITO Film Deposition

The first transparent electrode to be developed was a tin oxide (SnO_2) film called the NESA film. Although the film's ability to be formed in the atmosphere is a plus, the film has given way to ITO because of difficulties in etching it. At present, ITO is used as transparent electrodes in virtually all LCDs. ITO film can be formed either in a vacuum or under non-vacuum conditions. Figure 3.40 shows representative ITO-film production methods. In the following, we describe a vacuum deposition method and a sputtering method, which are representative vacuum formation methods; and a pyrosol method, which affords an alternative to vacuum formation.

(1) Vacuum deposition method

The vacuum deposition method uses sintered ITO as a starting material. The raw material is heated in a vacuum. ITO is vaporized and deposited onto a glass substrate. Despite the name vacuum deposition method, a small amount of oxygen is introduced into the reaction chamber

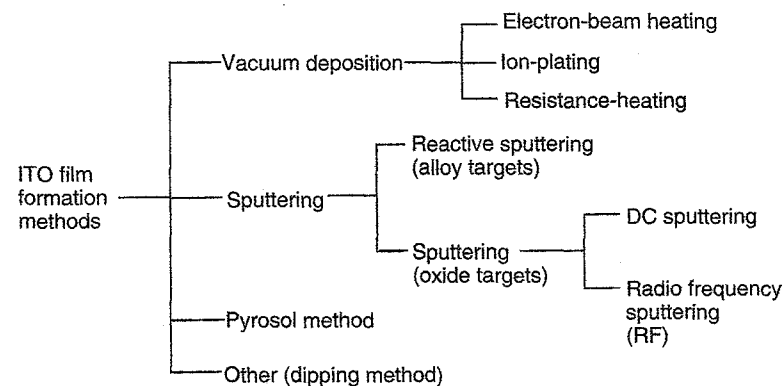


Figure 3.40 Classification of ITO film formation methods

in order to control the rate at which the ITO film crystallizes and becomes oxidized. Because the temperature of the glass substrate during the vaporization process influences the quality of the resulting ITO film in subtle ways, the temperature must also be controlled precisely. These controls give one the ability to regulate both the resistivity of the film and the grain size of the ITO crystals that are formed on the substrate.

Techniques employed in the vacuum deposition method for vaporizing ITO include resistance-heating and electron beam (EB) heating, shown in Figure 3.41. The EB vapor-deposition produces a relatively smooth ITO surface. Resistance-heating results in a rough surface. In either case, the actual grain size achieved ranges from 500 Å to 1500 Å. A drawback of the vacuum deposition method, however, is that, being a point-source deposition method, it is not the best method for producing a uniform film thickness when applied to a large area.

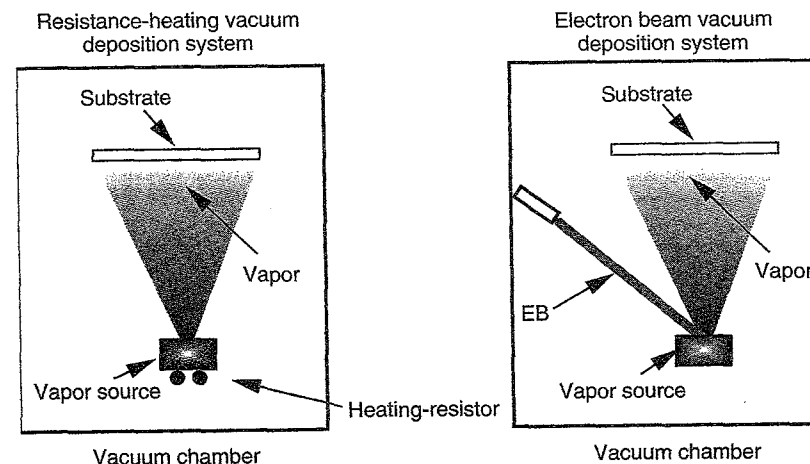


Figure 3.41 Concept of a vacuum deposition system

In any ITO film-formation method, heating the substrate to 500°C increases the conductivity of ITO by a factor of 2.5 to 3, compared with the case where the substrate temperature is held at room temperature. Thus, controlling the substrate temperature is a critical condition for reducing the resistance. The resistance-temperature function is a step function, and can be divided into four steps: room temperature - 180°C, 180°C - 250°C, 250°C - 300°C, and over 300°C. When heated at 300°C or greater, glass substrate requires an operation called annealing (releasing the strain by heat treatment) in order to remove the thermal stress produced by the heating. Because the materials composing a color filter are organic substances, the upper limit on heat treatment is about 250°C. Manufacturing ITO electrodes for STN color filters, which require an ITO sheet resistance of 10 $\Omega/\square$, requires heating at 250°C. By contrast, producing ITO electrodes for TFT color filters, for which an ITO resistance of 100 $\Omega/\square$ is adequate, only requires heating at 180°C. Therefore, STN and TFT color filters have different heat-tolerance standards. Generally, a substrate-heating temperature of 300°C and an ITO film thickness of 1000 Å result in a specific resistance of 1.7 - 3.0 $\times 10^{-4}$ $\Omega\text{-cm}$ and a sheet resistance of 17 - 30 $\Omega/\square$.

Units of resistance that are employed include sheet resistance R ($\Omega/\square$), in addition to the specific resistance ρ ($\Omega\text{-cm}$) of film. Equation 3.1 expresses the relationship between these parameters and film thickness d (Å):

$$\rho = R \cdot d \times 10^{-8} \quad (3.1)$$

(2) Sputtering method

The sputtering method can broadly be divided into the

reactive sputtering method and the sputtering method that uses oxide targets. Because it uses an area-source sintered raw material, the sputtering method is considered to be superior to the vacuum deposition method in uniformity of film thickness.

The reactive sputtering method produces a semi-transparent film on a glass substrate by sputtering a target composed of an alloy of indium and tin in a gas mixture of argon and oxygen, and renders the film transparent by heat-treating it either in the atmosphere or under an inert gas. Under this method, a thick film does not readily lend itself to transparency-processing, and the specific resistance can vary significantly as a function of the rate of film formation. Because of these drawbacks, the reactive sputtering method has largely been replaced by sputtering from oxide targets.

As shown in Figure 3.42, sputtering from oxide targets involves generating a plasma by means of a gas mixture

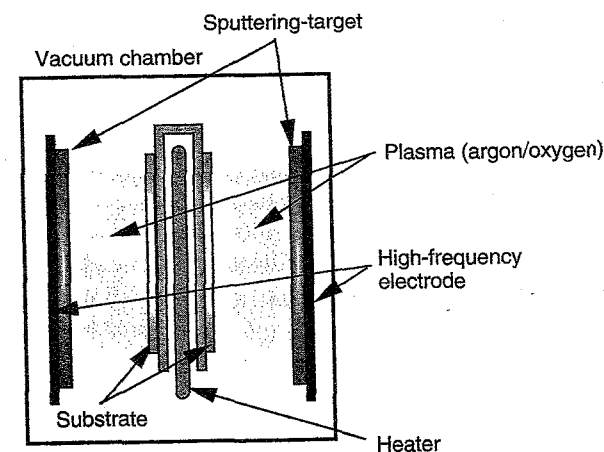


Figure 3.42 Conceptual diagram of an RF sputtering system

containing argon and a small amount of oxygen. The energy of the plasma is used to sublimate ITO from the target to produce an ITO film on a glass substrate. Recent developments have permitted adding hydrogen and water to the gas mixture and precisely controlling the reaction conditions in order to regulate the resistance of the resulting film. For a film thickness of 200-300 Å, a resistance of $2.0 - 2.5 \times 10^{-4} \Omega\cdot\text{cm}$ can be produced. For a film thickness of 1000 Å, the resulting resistance is $1.7 - 2.0 \times 10^{-4} \Omega\cdot\text{cm}$. The sputtering method offers the additional advantages of a fast etching rate of the ITO film that is produced and a short deposition time. Because of a low specific resistance variability, sputtering is the method of choice for producing ITO film for TFT LCDs.

(3) Pyrosol method

The pyrosol method refers to the technique of forming a film by producing, by means of ultrasonic waves, an aerosol of fine particles of organo-metallic compounds of indium and tin, spraying the aerosol onto a glass substrate that is heated at 500°C, and thermally decomposing the compounds (Figure 3.43). The ITO films made by the pyrosol

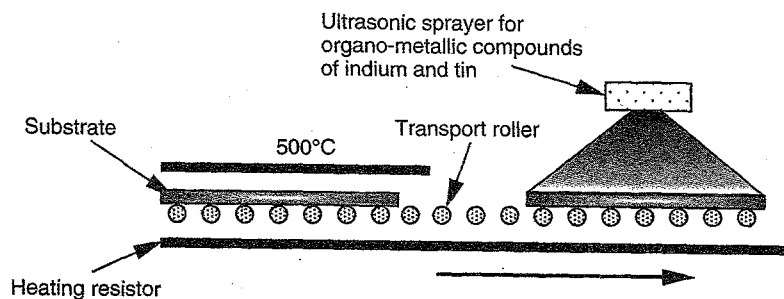


Figure 3.43 Conceptual diagram of a pyrosol system #1 substrate

method offer excellent etching properties while suffering from low thermal stability. Another drawback is that the high glass substrate temperature that is required limits the types of substrates to which the technique can be applied. The pyrosol method is capable of producing a specific resistance of $4.0 \times 10^{-4} \Omega\cdot\text{cm}$ for a film thickness of 1000 Å.

3.5.3 ITO Film Properties

The properties of ITO films that must be addressed include: sheet resistance, optical transmittance, heat resistance, alkali-resistance, etching characteristics, electrochemical stability, film-surface profile, bonding strength, film hardness, film thickness, and external appearance (scratches, stains, foreign objects, pinholes, etc.). Among these, sheet resistance, optical transmittance, etching characteristics, and heat resistance are especially important. These properties are discussed below.

(1) Sheet resistance

Different display methods (STN vs. TFT) and different mounting sites (top vs. bottom substrate) require different area resistance values. These differences are summarized in Table 3.4. Because in passive matrix devices, represented

TABLE 3.4 Properties of ITO for different applications

	STN		TFT	
	SIGNAL ELECTRODE	SCANNING ELECTRODE	TFT ARRAY	COMMON ELECTRODE
Sheet resistance ($\Omega/\square$)	7~15	7~15	7~15	Approx. 100
Film thickness (Å)	1500	2500	500~1000	700
Film deposition temperature (°C)	250	250	300	130

by STN, the pixels and electrodes are made with ITO film, only these devices require ITO films of a low specific resistance. Therefore, for these devices ITO films of a 7 - 15 $\Omega/\square$ resistance are used. TFT devices also require a sheet resistance of 7 - 15 $\Omega/\square$. An important requirement is a low resistance variability as well as a low absolute value of resistance. Variability in resistance can result in uneven displays. Common electrodes mounted on the color filter substrate side for a TFT LCD require a sheet resistance of 100 $\Omega/\square$. However, the common-reversal drive method requires a sheet resistance of less than 10 $\Omega/\square$ for this electrode. TFT display electrodes require an ITO film thickness of 500-1000 Å; color filter electrodes require an ITO film thickness of 1000-1500 Å.

(2) Optical transmittance

To ensure the reproduction of as natural-looking colors as possible, the optical transmittance should be flat in the visible-light region. The optical transmittance of ITO film is liable to change when the film is subjected to heat treatment in subsequent production steps. This is accounted for by making the film as thin as possible. However, as a general rule, the thinner an ITO film, the higher is its resistivity. Reportedly, the reason for this phenomenon is that the greater the film thickness, the greater is the extent of diffusion of oxygen into the film, thus eliminating oxygen defects throughout the film. A similar degradation of optical properties is observed when thin films of polyimide are heated.

The optical transmittance of the ITO layer must also be taken into consideration for setting colors for the color filter. Because of a difference in refractive index, the type of interference shown in Figure 3.44 occurs between glass and ITO.

If the thickness is an integral multiple of the wavelength, the extent of interference varies with the thickness of the film. To exploit this fact and to prevent a loss of optical transmittance on the blue side, the thickness of the ITO film should be set at $490 \text{ nm} \times 1/2 (=245 \text{ nm})$ or $490 \text{ nm} \times 1/4 (=122.5 \text{ nm})$. In this case, the resistance of ITO varies in direct proportion to the film thickness. Therefore, as noted previously, the film thickness should be set so as to achieve the optimum light transmittance, as well as to control the resistance by regulating the temperature at which the substrate is heated in the film deposition process. As a general rule, a minimum light transmittance of 78% is required. In view of the fact that the transmittance of glass is 90-92%, this seems to be an attainable value for mass production purposes.

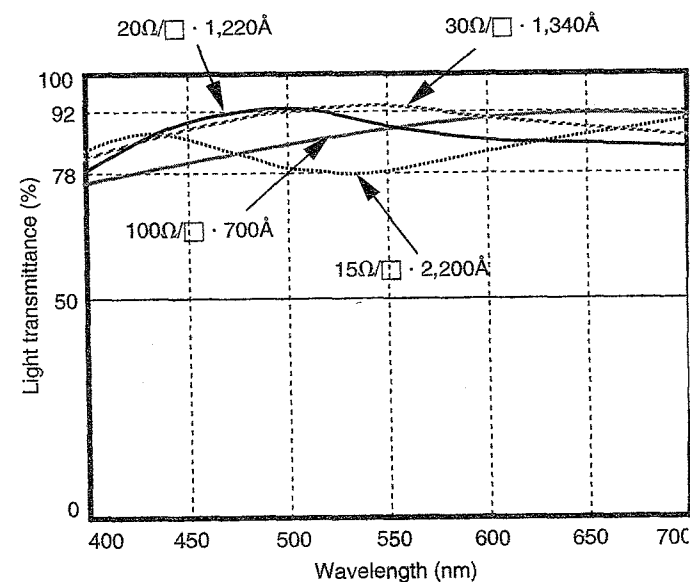


Figure 3.44 Relationship between ITO light transmittance, film thickness, and resistance

(3) Chemical stability

The desirable moisture-resistance is $\pm 10\%$ or less change in measured film properties when the film is allowed to stand for 24 hours at 60°C and 90% RH. As for alkali resistance, the film should not undergo a greater than 10% change in its film properties when the film is cleaned with an alkaline cleaning agent or is subjected to patterning operations.

(4) Film surface physical parameters

Generally, the greater the film thickness, the greater is the grain size. This makes the film surface rough. Although increases in the grain size improve the etching properties of the film, they can adversely affect the orientation film processing. Because of this fact, the ITO film for most applications is produced by sputtering from an oxide target.

(5) Etching characteristics

The ITO used on a TFT array substrate must be patterned uniformly as pixel electrodes through etching. For wet-etching, an etchant composed of ferric chloride and hydrochloric acid is normally used. The etching process is controlled in terms of chemical composition, temperature, and time. The typical etching rates achieved using an etchant heated at 40°C are: $200\text{\AA}/\text{minute}$ for a reactive-sputtered film; $600\text{\AA}-700\text{\AA}/\text{minute}$ for an oxide-target-sputtered film; and $700\text{\AA}-800\text{\AA}/\text{minute}$ for a pyrosol-produced film. As a general rule, an etchant based on ferric chloride and hydrochloric acid attains the maximum etching rate when the concentration of hydrochloric acid in the etchant is 70-80 vol. %.

(6) Thermal resistance

Due to the fact that the colors that make up a color filter are not highly heat-resistant, most ITO films for color filters are produced by low-temperature sputtering. Therefore, the color filter's heat-tolerance determines the maximum temperature that can be applied to ITO. Normally, color filters that employ pigments have a heat tolerance of 180°C . Therefore, when subjected to orientation film curing, the ITO film must remain stable at this temperature. The maximum temperature to which a TFT array substrate is subjected occurs during the gate-insulator deposition process ($350^\circ\text{C}-400^\circ\text{C}$). However, because the ITO film is deposited after this process, the high-temperature processes that the ITO film must undergo are the SiN_x passivation film deposition process (approximately 250°C) and the orientation film curing process (180°C). Therefore, the ITO film must be able to withstand these temperatures. The ITO film for STN LCDs requires a heat tolerance up to $250^\circ\text{C}-300^\circ\text{C}$, which is the temperature range for the orientation film curing process.

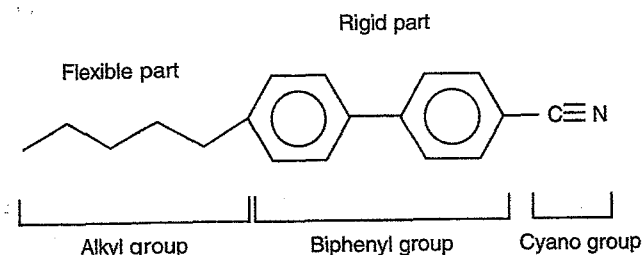


Figure 3.45 Example of a liquid crystal molecular structure

3.6 LIQUID CRYSTAL MATERIALS

As shown in Figure 3.45, the representative structure of a nematic liquid crystal contains a flexible component, such as an alkyl group, and a rigid component, such as a benzene ring. These components are responsible for producing liquid crystal properties, as discussed in Chapter 2. However, to obtain the desired set of properties, normally several liquid crystals are blended. The physical properties required of such a mixture depend on the type of application for which the nematic liquid crystal is intended.

The Van der Waals force and a repulsive force act between liquid crystals. The directions and magnitude of these forces dictate whether a given mixture of liquid crystals become a smectic liquid crystal phase or a nematic liquid crystal phase. The occurrence of a phase is largely influenced by the molecular structure as well as by the temperature. In these liquid crystal phases, the interaction between liquid crystal molecules causes an alignment of the molecules' directors, and this produces various types of anisotropies. The anisotropy of the liquid crystal molecule dielectric constant is primarily attributable to the Freedericksz transition, in which liquid crystals are re-oriented due to the effects of an electric field. The magnitude of the Freedericksz transition that is produced is also determined by the molecular structure. The dielectric constant in the direction of the long axis of a liquid crystal molecule minus the dielectric constant at a right angle to the long axis is called dielectric constant anisotropy ($\Delta\epsilon$). A nematic liquid crystal that has a positive dielectric constant anisotropy is called a p-type nematic liquid crystal. One that has a negative dielectric constant anisotropy is called an n-type nematic liquid crystal. p-type nematic liquid

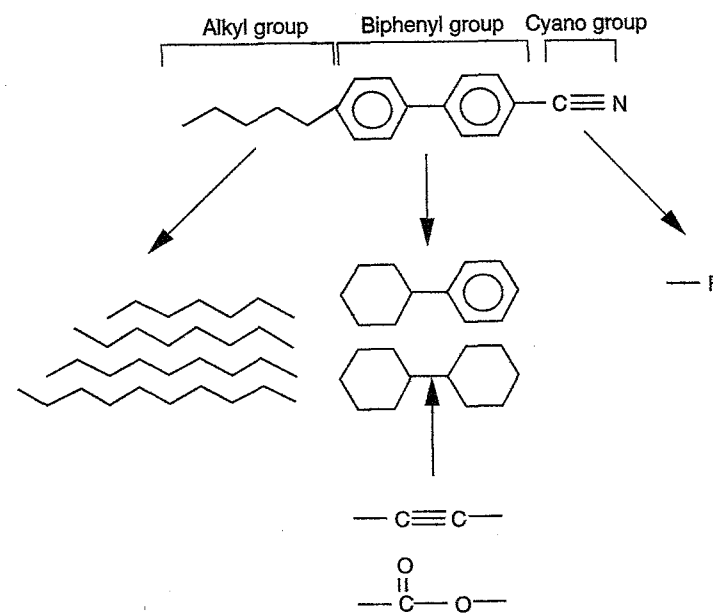


Figure 3.46 Structural design for a liquid crystal molecule

crystals are used in both TN and STN LCDs.

Figure 3.46 shows an example of a nematic liquid crystal molecular structure. This structure contains three basic parts: a cyano group, a biphenyl group with two benzene rings joined, and an alkyl group containing four to six carbon atoms. The cyano group serves to produce the positive dielectric constant anisotropy. The benzene rings exhibit the nematic phase property and supply π electrons to the cyano group. The alkyl group defines a smectic-phase onset temperature and contributes to the stability of the smectic phase. Molecular design efforts have involved replacing or modifying these three parts of a liquid crystal in order to synthesize new liquid crystals. New liquid crystals have been fashioned as a result of these efforts. The properties that cannot be produced by organic synthesis

can be produced by mixing various liquid crystals. Figure 3.47 shows a chronological sequence of production of liquid crystals through the replacement of parts, and the resulting performance characteristics. As indicated in the figure, replacing the biphenyl with a phenylcyclohexane and then with a dicyclohexane causes a shortage of π electrons and reductions in refractive index and viscosity. Increasing the length of the alkyl chain shifts the nematic-phase (4-6) onset region toward higher temperatures and induces the onset of the smectic phase (7 to 9 carbons). To increase chemical stability, attempts have been made to insert ethylene between biphenyls, and acetylene and

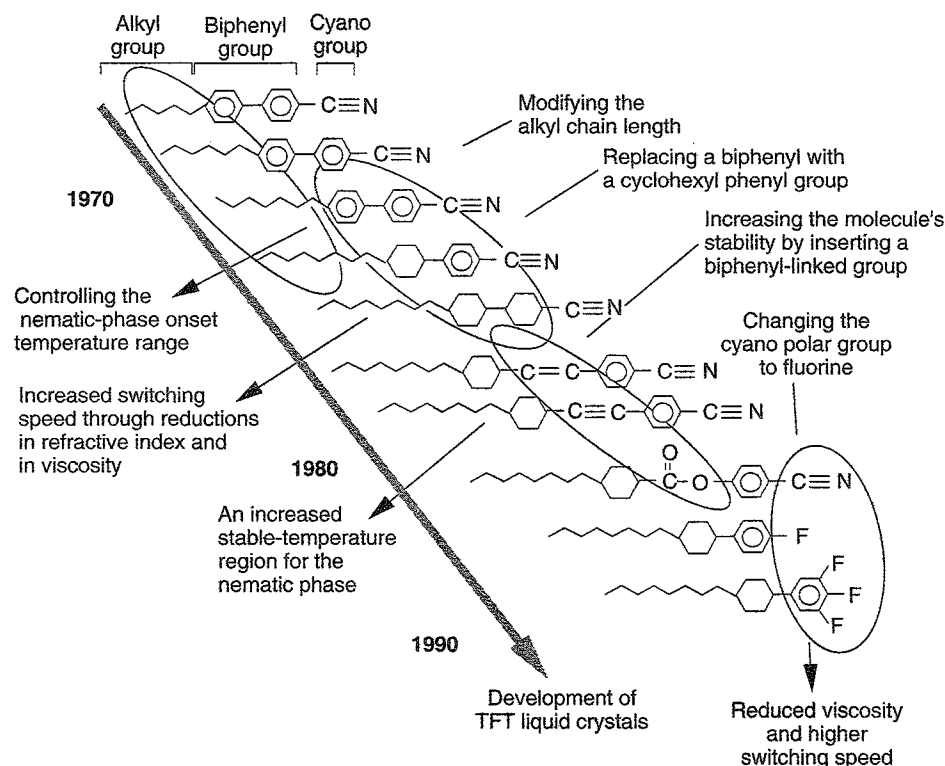


Figure 3.47 Molecular design for liquid crystal molecules

ester-linked molecules between benzene rings. Conversely, studies were conducted to increase the clearing temperature by increasing the number of benzene rings.

Recently, low-viscosity liquid crystals in which the cyano group is replaced by a fluorine atom have been developed. This breed of liquid crystals, which includes those incorporating multiple fluorine atoms and fluoro-methoxy groups, offers excellent stability while achieving both a low viscosity and a high refractive index anisotropy. These liquid crystals are blended for making TFT LCDs. A liquid crystal used in a TFT LCD display must meet the following performance characteristics: operating temperature range (phase stability), drive voltage (dielectric constant anisotropy and the coefficient of elasticity), display speed (viscosity and the coefficient of elasticity), contrast, color saturation (phase difference, birefringence), gray-shades, and viewing angle. Because no single liquid crystal can meet all these requirements, various liquid

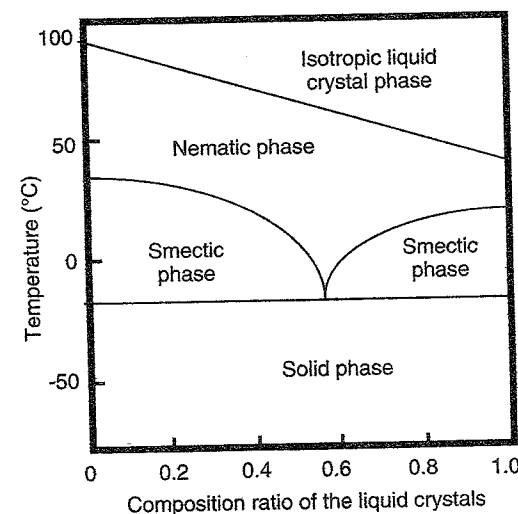


Figure 3.48 Phase diagram for a two-component liquid crystal

crystals are blended in order to make the best compromise. As shown in Figure 3.48, an advantage of blending is a wider area in which the nematic phase can remain stable, and this area is larger than the nematic-phase onset temperature region. Although blending can produce synergistic effects, not all performance characteristics can be improved. Therefore, it can be a daunting task to determine the best mixing ratios for the ten or so liquid crystal compounds that are normally blended.

Table 3.5 shows the attributes of liquid crystal mixtures that are used in LCDs. TN LCDs (used in TFT displays) and STN LCDs exhibit different performance characteristics.

3.7 ORIENTATION LAYER

3.7.1 Need for an Orientation Layer

The orientation film is essential to LCD displays. An LCD device displays images by using the dielectric constant

TABLE 3.5 Performance characteristics of LCDs for different applications

	STN		TFT	
	220° TWIST	240° TWIST	FIRST MINIMUM	FIRST MINIMUM
Design retardation (μm)	—	—	0.48	0.48
Refractive index n_e	1.616	1.611	1.555	1.562
Δn	0.122	0.120	0.086	0.089
Phase-transition temperature (°C)				
Sm-Ne	-40	-40	-40	-40
Ne-isotropy (°C)	86	85	85	110
dielectric constant anisotropy, $\Delta\epsilon$	10.6	5.9	7.9	7.7
Threshold voltage (V)	1.99	2.72	1.48	1.76

anisotropy of liquid crystal molecules and by changing their orientation through the application of a voltage. A critical element of an LCD device is the ability to control the orientation and the pretilt angle of the liquid crystal molecules for a given operating mode. The orientation film is designed to perform these functions.

As was discussed in Chapter 2, in a TFT color display using the TN mode, the orientation of the liquid crystal molecules is gradually twisted 90° as the molecules extend from the TFT array substrate to the color filter substrate. In the absence of an external influence, liquid crystal molecules are oriented in random directions. Therefore, something must be done in order to produce a 90° twist angle.

As shown in Figure 3.49, on an untreated glass substrate the liquid crystal molecules are oriented in random directions. Figure 3.50 shows an example in which the surface of a glass substrate is coated with an organic film, and liquid crystals are aligned on the orientation film, which is rubbed in one direction (more on this later). When so treated, the liquid crystals orient themselves uniformly in the direction of the rubbing operation. This is precisely the function of the orientation film.

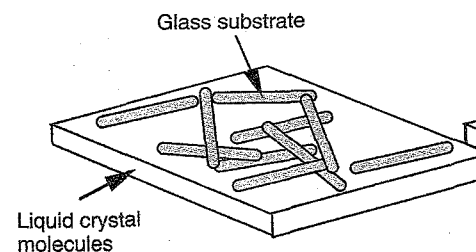


Figure 3.49 Liquid crystals on a glass substrate

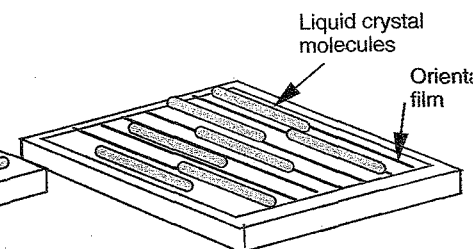


Figure 3.50 Liquid crystals on an orientation film

If the orientation films coated on the top and bottom substrates are parallel to each other, the liquid crystal molecules also align themselves in parallel, as shown in Figure 3.51. When one orientation film is turned at a right angle to the other orientation film, as shown in Figure 3.52, the liquid crystals become aligned in a vertical direction on the bottom orientation film and in a horizontal direction on the top orientation film. The result is an exact 90° twisting of the liquid crystals as they extend from the bottom orientation film to the top. Therefore, to twist the liquid crystals, it

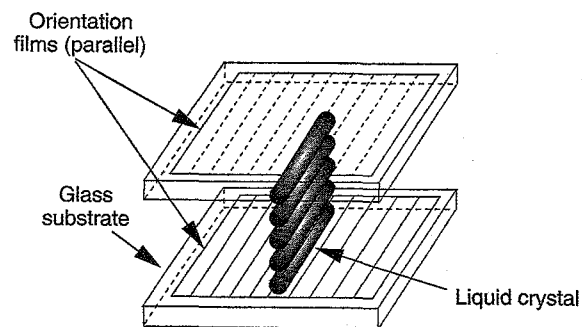


Figure 3.51 Parallel alignment of liquid crystals

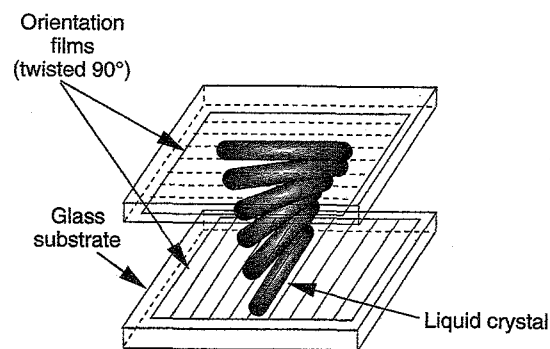


Figure 3.52 Twisted alignment of liquid crystals

suffices to orient the TFT array substrate 90° relative to the color filter substrate. The question that remains is, how can we control the direction in which the liquid crystals become twisted (clockwise vs. counterclockwise)?

3.7.2 Controlling the Twist Angle

Imagine that the liquid crystal layer in a TN-mode LCD is sliced sequentially from top to bottom. Then, it will be seen that the liquid crystal molecules comprising the layer rotate little by little, and twist a total of 90° between the top and bottom glass substrates. If the orientation films on the top and bottom substrates are rubbed at exactly 90° to each other, and the pretilt angle (described in the next section) of the long axis of liquid crystals relative to a substrate is 0° , some liquid crystal molecules are turned 180° . Because of this, some liquid crystal molecules rotate clockwise and others counterclockwise (those with $+90^\circ$ and -90° twist angles). If this state of affairs is not altered, a mixture of positive-twist and reverse-twist regions results. The

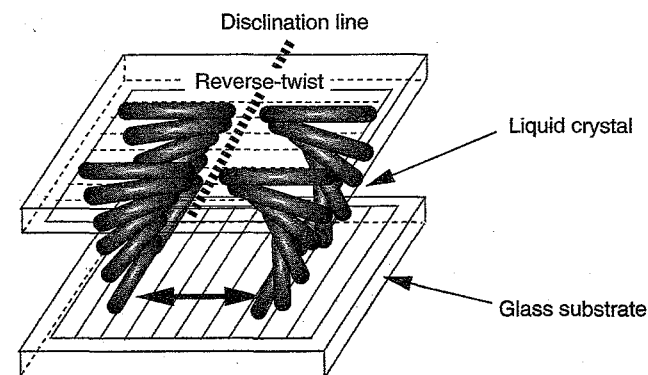


Figure 3.53 Reverse-twist of liquid crystals

reverse-twist region refers to a region in which the liquid crystal molecules rotate in the reverse direction, resulting in a reversal of the angle-dependency of optical transmittance. In such a mixture, a line of disclination occurs at the boundary between the regions (Figure 3.53). In effect, disclination renders the liquid crystals polycrystalline rather than monocrystalline. The disclination produces white light and thus reduces contrast.

A common technique employed to prevent this problem involves adding to the liquid crystals a chiral agent that has a pre-twisted molecular structure, so as to confer either a clockwise or a counterclockwise rotation propensity on the liquid crystal molecules. In some cases, chiral nematic liquid crystals are added, in which the nematic liquid crystals themselves are endowed with a chiral structure. Another useful technique, which seems to have given way to other methods, is to reduce the rubbing directions for the top and bottom substrates to an angle less than 90° . A modest pretilt angle (several degrees) of the long axis of liquid crystals causes the orientation of the liquid crystal long axis and the direction of the inclination of the long axis to propagate to the liquid crystal layer even if the top and bottom substrates are rubbed at exactly 90° to each other. In this case, the liquid crystals twist only in one direction. Therefore, the direction of the pretilt inclination, which is determined by the rubbing operation, must be controlled so that it matches the twist angle induced by the chiral agent that is used.

3.7.3 Pretilt Angle

As described above, a rubbing operation performed on an orientation film causes the long axes of liquid crystals to

align themselves horizontally (homogeneously) on the orientation film, parallel to the direction of rubbing. In this case, the thin, elongated liquid crystal inclines by the angle α on the orientation film, with one end of the liquid crystal rising from the orientation film so that the angle α is formed between the liquid crystal and the orientation film. This angle, α , is referred to as the pretilt angle. As a rule, rubbing operations produce a pretilt angle of $1\text{--}7^\circ$.

If the angle α is 0° , applying a voltage to the nematic liquid crystal causes the liquid crystal's long axis to align itself in the direction of the electric field (perpendicular to the substrate). In this case, the liquid crystal can rise either from the right or from the left, as illustrated in Figure 3.54. Therefore, the application of a voltage can produce regions of opposite tilt directions (reverse tilt). In this case also, a disclination occurs on the boundary between the two regions, with the undesirable effects of reduced contrast and residual images. Fortunately, rubbing a polyimide orientation film creates a modest amount of pretilt angle. For high-density TFT LCDs, however, the pretilt angle thus formed must be increased to some extent. High-density

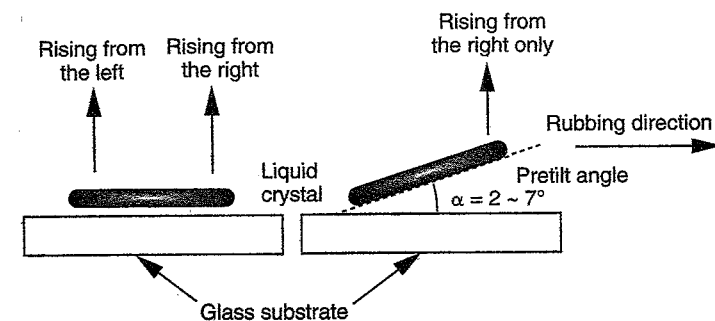


Figure 3.54 Pretilt angle of a liquid crystal

displays require increasingly smaller pixels. In such pixels, the horizontal electric field that occurs between buslines (electrode wires) in the vicinity of a display electrode can reverse the tilt angle, thus inducing a disclination. Although the decreased contrast associated with the disclination can be prevented by covering the area around the display electrode by increasing the width of the color filter black matrix, this measure also reduces the aperture, with an attendant decrease in the brightness of display. To prevent this problem and to minimize the occurrence of reverse tilt, the pretilt angle α is normally increased to about 5° .

3.7.4 Alignment Using Only Orientation Layer

Just applying an orientation film does not force liquid crystals to align themselves in one direction. Some treatment is required to create a film that is anisotropic in orientation. The rubbing process achieves this goal.

3.7.5 Rubbing Process

"Rubbing" refers to the technique of rubbing an orientation film in one direction, normally by using a piece of soft cloth. The mechanism by which rubbing causes the liquid crystals to align themselves has gradually become better understood. Theories that attempt to explain the effects of rubbing operations include: alignment of liquid crystals due to intermolecular forces, such as the Van der Waals force; and the stretching of the orientation film due to a rubbing-induced shearing stress, causing the direction of the long axes of orientation film molecules and the direction of the long axes of liquid crystal molecules to coincide,

thus creating a stable energy state. The second theory is thought to be more germane.

In the actual orientation process, a piece of rubbing material made with nylon or cotton velvet is fastened around a roller, the roller is rotated, and the glass substrate placed on the table is moved in the direction opposite the roller's spinning direction. Figure 3.55 shows a conceptual diagram of this operation. The operating conditions that affect the outcome of a rubbing operation include: the properties of the fiber that compose the rubbing cloth, the extent to which the fiber is pressed (actually, the extent to which the fiber is bent), the roller spinning speed, the substrate transport rate, the number of rubbing operations performed, and the rubbing pressure applied. These conditions are controlled by trial and error. Among the LCD fabrication processes, the rubbing operation requires a particularly high level of specialized expertise.

The rubbing process, which is a physical process, generates static electricity from the glass substrate surfaces and particles from the rubbing cloth and the polyimide.

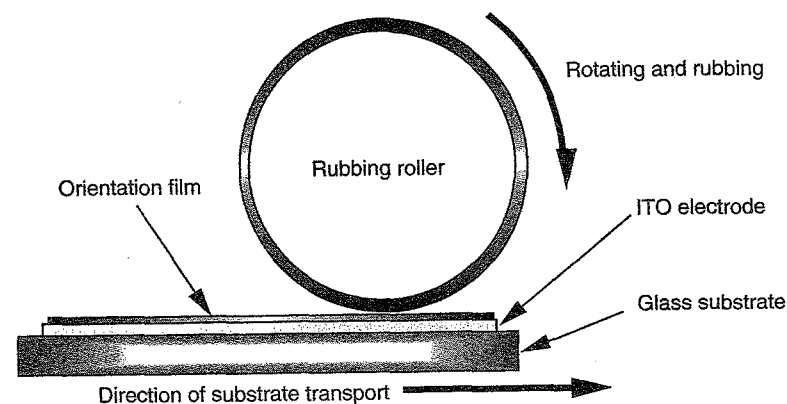


Figure 3.55 Conceptual diagram of the rubbing operation

Furthermore, the roller axis and the table must be aligned parallel within a ± 0.01 mm tolerance. Therefore, rubbing a large area in a uniform manner can be a daunting task from a mechanical design standpoint. Given the technical hurdles associated with the rubbing process, are there any other ways to align liquid crystals?

Alternatives to rubbing have long been a subject of research. One technique that has been developed involves vapor-depositing silica (SiO_2) from an oblique angle and aligning the liquid crystals along the grooves that are created between the silica crystals. A drawback of this oblique vapor deposition surface-treatment method (Figure 3.56) is a limited processing capacity. Therefore, this method is not currently used. Newer approaches include a laser-polymerization-based orientation film formation method, and the Langmuir Blodgett (LB) technique, in which a film of molecules that are oriented in one direction, such as a surfactant floating on the water surface, is scooped up onto a glass substrate in a specified direction. Further research is needed on these and other techniques as alternatives to the rubbing method.

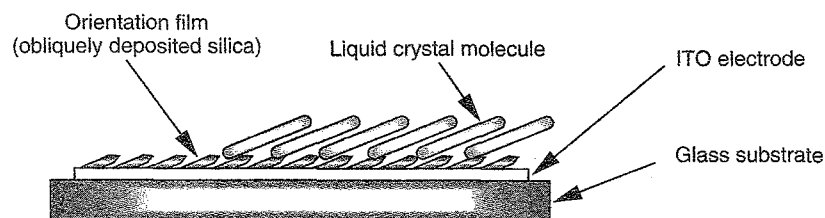


Figure 3.56 Conceptual diagram of the orientation of liquid crystals on a film made by oblique vapor-deposition of silica

Another technique that is being investigated for improving the viewing angle for LCD displays involves generating a random orientation of liquid crystals in the pixels without performing rubbing operations. Although polyimide orientation films would be used, rubbing would not be required. In this technique, the liquid crystal material is injected into the liquid crystal cell at a temperature that turns the liquid crystal material into an isotropic liquid. As shown in Figure 3.57, at ordinary temperatures the liquid crystal molecules assume a random orientation state, thus creating a multidomain state, in which clusters of liquid crystals of the same orientation (multidomain) occur randomly. The random orientation of liquid crystal molecules in all directions improves the viewing angle. As explained in Chapter 2, this liquid crystal alignment can also display images by using phase differences in TN liquid crystals. Therefore, TN-mode optical properties are produced under the condition that the incident angle of linearly polarized light and the long axis of liquid crystal molecules form random angles. There are many other non-rubbing orientation methods that merit consideration.

3.7.6 Polyimide Orientation Films

Polyimide is obtained by the thermal polymerization (250°C or higher) of polyamic acid. The solution used for

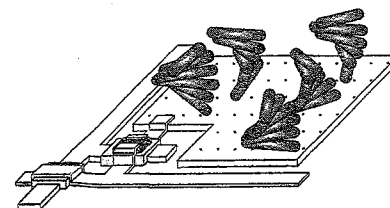


Figure 3.57 Multidomains

orientation films is composed of polyamic acid added to the following mixture of solvents: an amido-based polar solvent, such as N-methyl-2-pyrrolidone (NMP) for solubilizing the imido constituents, and cellosolve acetate solvent that enhances the coating property. Because they avidly take up water under high-temperature conditions, coating liquids for polyimide-based orientation films should be refrigerated and stored in a dark room.

The process of converting polyamic acid into polyimide is called imidization. The temperature required for imidization is called the imidization temperature. The imidization rate refers to the percentage of the starting material that has been imidized. Pre-imidized polyimide (soluble polyimide) is commercially available. Off-the-shelf polyimide can be used to make a polyimide orientation film just by coating and drying (at 180°C or less). Most commercially available orientation films are made of polyimide. On many color TFT LCDs, pre-imidized polyimide (soluble polyimide) is used.

What are the advantages of using polyimide as an orientation film? An orientation film must meet the following requirements: amenability to orientation, ease of coating, a high bond strength, the capability of pretilt angle control, and compatibility with the liquid crystal material. Overall, the polyimide orientation film ranks high on these aspects for the following reasons:

- (1) High thermal stability, up to 300°C
- (2) A transparent material with a high glass transition temperature (T_g)
- (3) A high degree of affinity to the liquid crystal, with a great capacity to align liquid crystals without reacting with them

(4) A high bond strength to substrates and ITO electrode layers, thus facilitating orientation processing

The glass transition temperature T_g is a physical constant that characterizes a polymer. The higher this temperature, the greater is the intermolecular cohesive energy, i.e., intermolecular force. Also, the higher the glass transition temperature, the greater is the intramolecular force. Therefore, even if an orientation film has rigid molecular chains, its glass transition temperature can be an index indicating the physical strength of the film. Polyimide is the only film material that satisfies the basic functional requirements for an orientation film. Only a few polymers can withstand temperatures up to 300°C. Of these polymers, only polyimide can be made into a transparent film.

3.7.7 Properties of the Orientation Film

In terms of the fabrication process for TFT color displays and of display quality, several attributes of an orientation film are desirable. They are identified as follows:

- (1) Uniform coating
- (2) Adequate film strength to withstand rubbing operations, and a strong bonding to the base materials (ITO film, TFT devices, metal conductors, color filters, and sealant)
- (3) Stability relative to the chemicals that are used in the cleaning process
- (4) A high stability relative to the liquid crystal-sealing operation and the seal-hole closing operation.

For the coating operation, recent advances in fabrication equipment technology have produced roll coaters that are capable of applying a uniform coating.

For bonding, because polyimide itself is a poor bonding material, often silane-coupling agents and other bonding

enhancers are often added. Recently, self-bonding polyimide incorporating siloxane-linkages has become commercially available. This, combined with the UV-cleaning of substrates, has virtually solved the problem of adhesion.

Chemical resistance is not a problem with polyimide. For orientation stability, an important requirement is that there is no degeneration of orientation when the TFT array and the color filter substrate are sealed together. Because of the limited thermal tolerance of the color filter, the orientation film must be formed at low temperatures (less than 180°C). To meet this requirement, pre-imidized polyimide (soluble polyimide) orientation films have been developed.

Adequate display quality requires two sets of functional properties in an orientation film:

- (1) Properties related to the orientation of liquid crystals
- (2) Physical properties of the orientation film itself

Among the critical parameters that are related to the orientation of liquid crystals are the aligning force that aligns the liquid crystals, and the pretilt angle controlling force.

Whereas earlier TFT color LCDs required a pretilt angle of 1-2°, higher-density displays require greater angles in the range of 2° to 7°.

This is because the increase in the TFT interconnect density resulting from increases in the pixel density of the LCD have reduced the distance between pixel electrodes on the one hand and signal and scanning lines on the other. The reduced distance increases the effect of the horizontal electric field that arises between the electrodes and the lines, which can result in the occurrence of alignment defects (locally reversed tilt angles) called reverse-tilt domains (Figure 3.58). An increased pretilt angle is necessary to prevent this problem.

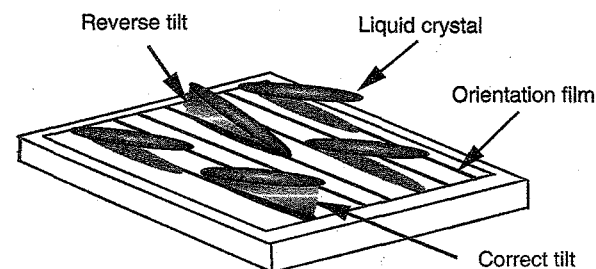


Figure 3.58 Occurrence of a reverse tilt

Alignment defects can produce disclinations and cause a hysteresis before and after a drive voltage is applied. This problem can lead to a reduced contrast and to residual images. A high pretilt angle is necessary to prevent reverse tilt. Specifically, the pretilt angle is controlled by modifying the polyimide film material and by regulating the baking temperature.

Currently the focus of efforts is on the development of an orientation process for producing a wide viewing angle. Ideas that have been advanced toward this end include a double-layer orientation film containing high and low pretilt angles; and, creating two regions of opposite pretilt directions within a pixel through the use of a mask-rubbing technique.

The physical parameters that characterize an orientation film include optical properties and electrical properties. Optically, an orientation film should be neutral so that it does not affect the transmittance or the chromaticity of display. In many polyimide films, the light transmittance declines rapidly when the wavelength of light is 500 nm or less, causing the film to become brown-colored. However, because the actual film that is applied is extremely thin, on

the order of 500 Å, any decrease in light transmission or increase in coloration can be ignored.

Several electric attributes need to be addressed. The voltage-holding capacity of the orientation film declines at high temperatures. The temperature rises to 50–60°C in the case of a display with backlight, and to 80°C in a display mounted in an automobile. An important requirement is that orientation films retain a high voltage-holding capacity even at high temperatures. Further, the problem of burn-in, wherein a displayed image becomes fixed on the screen, is thought to occur when DC voltage components remain after the AC pulses are applied to the liquid crystal. Therefore, orientation films must possess the characteristic that no residual DC voltage is retained on them. Another problem is that the presence of impurities and residual ionic substances in the orientation film can contaminate the liquid crystals, thus reducing their voltage-holding capacity. Therefore, the orientation film material must be purified to the same extent as the liquid crystal.

3.8 SPACERS

3.8.1 Necessity for Spacers

A color TFT LCD generates images by controlling the alignment of liquid crystals with a TFT and by varying the amount of light that is transmitted. For adequate display quality, it is essential to control the thickness of the liquid crystal layer for the LCD. The space between the glass substrates in which liquid crystals are stored, i.e., the thickness of the liquid crystal layer, is referred to as the cell gap. An irregular cell gap results in a local variation in the thickness of the liquid crystal layer (Figure 3.59), and produces

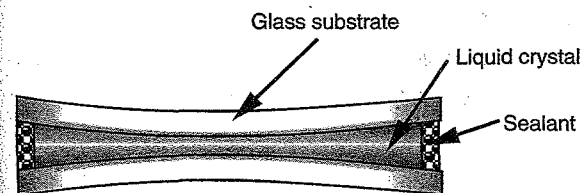


Figure 3.59 LCD without spacers

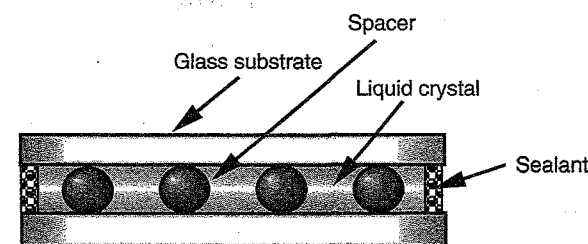


Figure 3.60 LCD with spacers

an uneven display. The cell gap is a critical factor determining the retardation $\Delta n d$, which is a fundamental optical parameter for liquid crystals. The retardation factor has a large bearing on the display characteristics of the LCD, including optical transmittance, contrast ratio, and response speed. Adequate control of the cell gap is an extremely important requirement.

Obviously, the first necessary condition for ensuring a uniform cell gap is to use flat glass substrates. Because the cell gap is extremely small, measuring only 5–6 μm , a common technique employed is to insert spacers that act as supporting columns between liquid crystal layers (Figure 3.60). Spacers are spherical particles composed of silica or polystyrene. One approach that is being investigated for enhancing the uniformity of the cell gap is to apply pressure to the cells to adjust the cell gap before and after liquid crystals are injected.

3.8.2 Why Spacers Don't Interfere With the Display

The smallest object that can be recognized by the human eye, or the resolution of the human eye, is approximately one minute in angle. Based on this fact, the minimum resolution in which the human eye can see objects on an LCD from a distance of 30 cm is approximately 30 μm . In other words, you cannot distinguish objects smaller than 30 μm that are at least 30 cm away from you. This limit, however, depends on both the brightness of the display and the brightness of ambient light. Since the cell gap for a color TFT LCD is only 5 μm , this sets the upper limit on the diameter of a spacer that can fit in the cell gap: also 5 μm . A spacer this small is below the detectable limit of the naked eye. Because they are invisible, the presence of spacers in a color TFT LCD does not interfere with the quality of LCD display. If spacers scatter light, however, they can slightly decrease the display contrast. This will be touched upon later.

3.8.3 Applying Spacers

How many spacers are needed to maintain a 5 μm cell gap for TFT color panels? As shown in Figure 3.61, let us con-

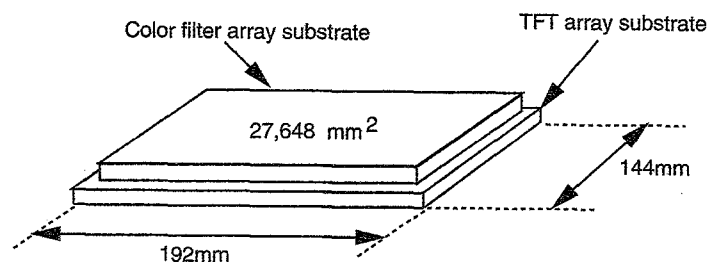


Figure 3.61 10-inch color TFT LCD

sider the TFT color LCD in a notebook PC. The area of LCD display is 192 mm vertically and 144 mm horizontally (= 27,648 mm^2) in the case of a VGA display mode with a pixel pitch of 0.3 mm. The greater the number of spacers used in a color TFT LCD, the higher is the resulting uniformity of the cell gap for the LCD. However, because too many spacers can degrade display quality, the judicious control of the number of spacers is of critical importance. The rule of thumb is to use a spacer density of 70 particles per square millimeter, which amounts to 2 million spacer particles for the entire panel. Since a panel contains 640×3 (RGB) $\times 480$ (= 921,600) sub-pixels (dots), there are approximately two spacers for each sub-pixel (Figure 3.62). The spraying techniques described below are employed for

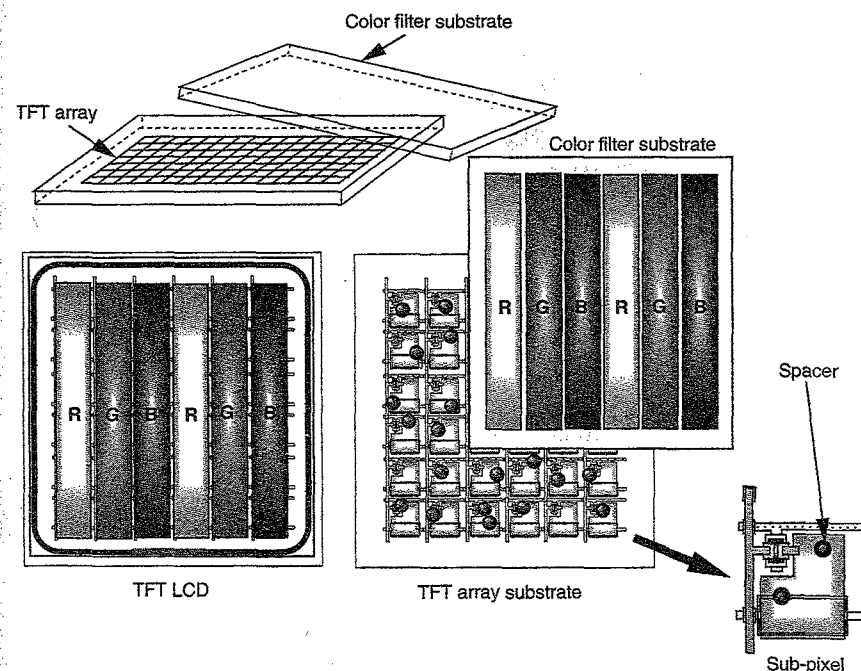


Figure 3.62 Spraying spacers

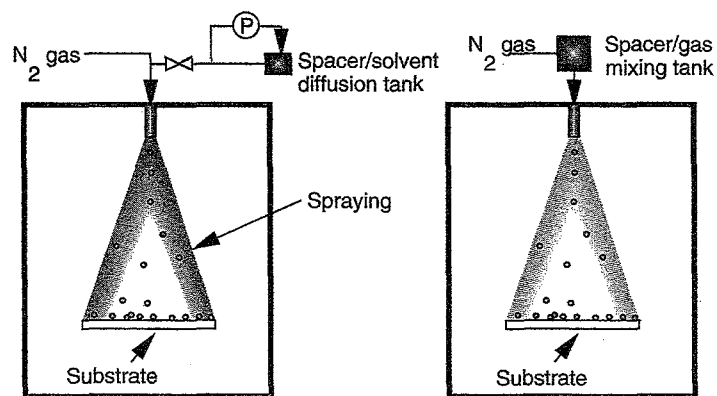


Figure 3.63 Wet spacer-spraying system

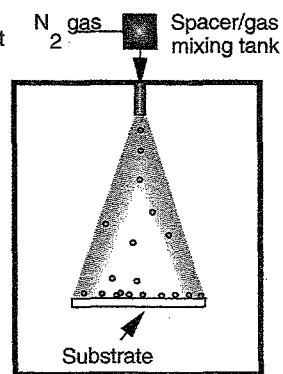


Figure 3.64 Dry spacer-spraying system

providing spacers in a liquid crystal cell in such large quantities and with great uniformity.

As shown in Figure 3.63, the wet method for spraying spacers involves the following steps: diffusing spacers in a low-boiling-point organic solvents, such as freon or alcohol, through the use of ultrasonic waves; spraying the spacer-diffused liquid; and drying the panel in order to evaporate the solvent. In the dry method, spacers are applied electrostatically or diffused by means of an air-jet (Figure 3.64). Important requirements are: producing uniform spraying over the entire substrate, controlling the spacer population (number of spacers per unit area), and preventing the formation of lumps. When TFT color LCDs are handled, measures should be taken to prevent a buildup of static electricity. In addition, freon, alcohol, and other organic solvents are subject to pollution control regulations. Because of this, the dry, air-jet diffusion method is the preferred method.

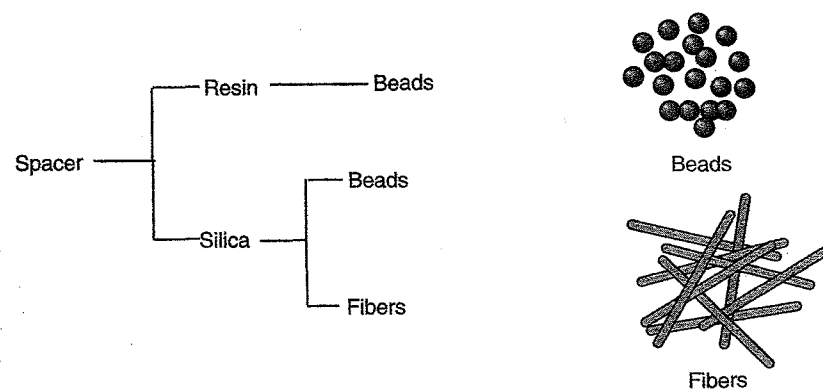


Figure 3.65 Classification of spacers

3.8.4 Spacer Properties

There are three types of spacers: resin-based spacers, silica-based spacers, and glass fiber-based spacers (Figure 3.65). Resin-based spacers are made from melamine, urea, benzoguanamine, or polystyrene resin. Since resin-based spacers are soft, their size can be changed by applying a weight. This permits a delicate control of cell thickness. Silica-based spacers, on the other hand, offer greater size stability and controlled particle-size distribution. In addition, they are less susceptible to electrostatic build-up than their resin-based cousins. Most of these resin- and silica-based spacers are spherical. In the past, fiber-shaped spacers were also used. Currently, most spacers are fashioned in bead-like spherical particles because of the ease with which they can be used to control the cell gap.

Spacers, which are often glass fibers, are also mixed into the edge sealant. To prevent the elution of alkaline constituents from glass, glass-fiber spacers are made of alkali-free glass by a spinning operation. The physical parameters of glass fibers that are used as spacers are:

diameter: 2-12 μm , length: 20-120 μm , and diameter deviation: ± 0.1 -0.2 μm .

3.8.5 Spherical Spacers

Let us examine how these small particles of a uniform size are made. A good example to review might be the fabrication of resin-based spacers. In one fabrication method, formaldehyde is reacted with either melamine or urea resin to produce an aqueous solution of amino resin; a curing catalyst, such as sulfuric acid, is added to the solution; and fine resin particles are produced by stirring the reaction mixture as polymerization occurs. Another fabrication method involves adding a reaction product of benzoguanamine resin and formaldehyde to an aqueous, colloidal solution of polyvinyl alcohol while stirring, and solidifying the colloidal suspension in the presence of a curing catalyst. This produces particles. For making these particular spacers, reaction conditions are controlled so that grains will not grow larger than a specified size during the polymerization process. For example, the rate of grain growth and the formation of particle nuclei are balanced by the selection of appropriate polymerization conditions so that particles will not become larger than a specified size. Also, during recrystallization using a solvent, the temperature and concentration are accurately controlled. After the reactions are completed, the spacers are centrifuged in order to separate the particles precisely according to their size.

3.8.6 Spacer Requirements

The following properties are required of spacers:

(1) Uniform particle size

Given the need to control the cell gap, this is an obvious requirement. A critical requirement is that the particle size does not change due to the effects of chemicals or heat treatment.

(2) Absence of contamination

Just like the orientation film, spacers come into direct contact with liquid crystal material. Therefore, spacers should be free of any impurities that could reduce the specific resistance of the liquid crystals.

(3) Maintaining an appropriate hardness

This is an important functional requirement from the standpoint of controlling the cell gap. Spacers must also possess an appropriate degree of elasticity in order to minimize damage to the TFT array or to reduce the possibility of foaming in a depressurized panel. A reduced pressure during LC injection can occur because of a difference in coefficient of thermal expansion between the liquid crystal that is maintained at a low temperature and the spacers.

(4) An appropriate coefficient of thermal expansion

To prevent any damage to the orientation film due to movements of spacers when the cell expands at high temperatures, the spacers' coefficient of thermal expansion should be close to that of the liquid crystal.

(5) Little decrease in contrast

Because an area occupied by a spacer is devoid of any liquid crystal, regardless of the drive state the area always

appears white. This slightly increases the brightness of the black level, and thus reduces contrast. One way to deal with this problem is to color the spacers in black.

In addition, thermal stability, dielectric constant, and refractive index are some of the parameters that must be addressed in selecting spacers.

3.9 SEALANT AND SEAL HOLE MATERIALS

3.9.1 Purpose of Sealant

Sealant is required in order to make a liquid crystal cell from two glass substrates. As shown in Figure 3.66, in addition to sealing the liquid crystal, sealant protects the liquid crystal from contamination from external sources, such as the intrusion of water, and from environmental changes. When used in an automobile or an airplane, an LCD is subject to temperature changes of 20 to 80°C. Without sealant, the slightest damage could render the whole color TFT display useless. Sealant is a critical component that protects liquid crystals from the thermal expansion of liquid crystal cells.

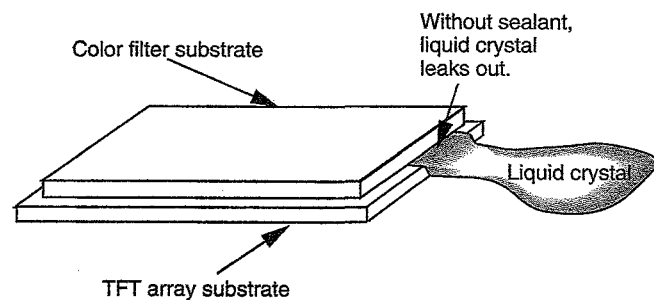


Figure 3.66 Sealing a color TFT LCD panel

3.9.2 Applying the Sealant

After constructing TFT arrays and color filters, applying a coating of orientation film, and spraying spacers, you are now ready to apply sealant. In most cases, sealant is applied in a rectangular, picture-frame-like pattern, either by means of screen-printing (Figure 3.67) or dispenser-drawing (Figure 3.68).

Screen printing offers superior production efficiency because patterns are created through a template. On the other hand, because the template touches the glass substrate directly, any contamination on the template can be transferred to the glass substrate, and foreign objects that are caught between the template and the glass substrate

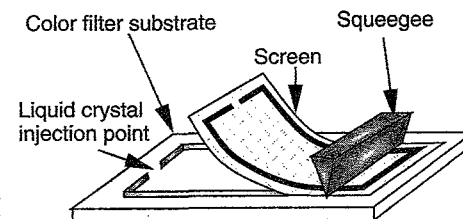


Figure 3.67 Applying sealant by screen-printing

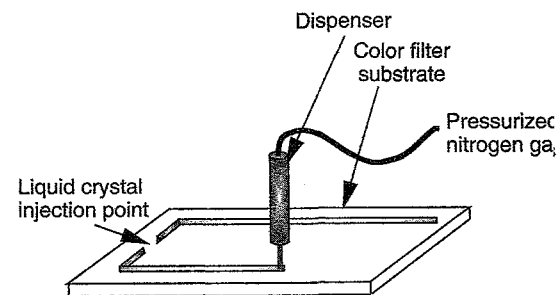


Figure 3.68 Applying sealant using a dispenser

can damage it. Therefore, the screen-printing method requires a high degree of contamination control.

The dispenser method avoids the contamination problem, but, in multi-panel production, in which many liquid crystal cells are cut out from a single piece of glass substrate, the dispenser method is lower in throughput than the screen-printing method. The dispenser method also requires delicate controls on the process for creating sealed corners with a constant width. With both advantages and disadvantages, the two methods compete in yield and productivity.

3.9.3 Kinds of Materials

Mainly thermosetting and UV-curing resins are used as sealants. Thermosetting resin includes two types: easy-to-use single-liquid resin, and the binary type, which requires mixing before it is applied. The single-liquid resin contains a curing agent. The binary type is used by mixing the main ingredient with a curing agent just before application. The main constituent material is either epoxy resin or phenol resin, both of which contain extensive cross linkages. Because these resins are liable to change as they get older, they must be stored at low temperatures.

Curing agents used are amines, carboxylic acid, and acid anhydrides. Heating and melting a curing agent causes a hardening reaction and transforms the liquid into a solidified resin. Amine-based curing agents require extensive heat treatment to prevent any adverse effect of the ingredients in the curing agents on the liquid crystal material.

Compared with thermosetting resins, UV-curing resins require a lower temperature for the hardening process. This minimizes the thermal expansion of the glass substrate and

permits high-precision alignment of substrates when the substrates are fixed together. UV light, however, cannot completely penetrate the resin. Therefore, heat-hardening is normally required after the UV-curing process.

A seal-hole material is used to close the injection inlet after liquid crystals are injected into an empty cell under a vacuum. Since the injection point is formed by sealant, it would seem that the same sealant could be used to close the hole. However, because before the seal-hole material is cured, it comes into contact with the liquid crystal, and both the spot to be sealed and the glass substrate are wet with liquid crystal, a separate agent is required to perform sealing. A mixture of highly pure silicone resin, UV-curing resin, epoxy resin, and acryl resin is normally used for the hole-closing purpose.

3.9.4 Material Properties

The important properties of sealants and seal-hole materials are as follows:

(1) *Reliable sealing*

Sealant must possess not only mechanical bonding strength, but also stability relative to environmental changes, such as temperature and humidity. It should have high enough bonding strength at 80-90°C. It should be free of any loss in bonding strength due to moisture absorption. It should be impregnable to water permeation and should not produce air leaks due to foaming or cracking.

(2) *Low curing temperature*

Previously, a sealant-curing temperature of 250°C was

acceptable. Current versions of color filter substrate require lower temperatures, less than 180°C , for color stability.

(3) *Absence of contamination of liquid crystal*

Sealant, or the curing agent that is used with it, should not contaminate the liquid crystal. The tolerable level of ionic impurities in sealants for TFT LCDs is on a scale of parts per billion, rather than parts per million. Because it comes into direct contact with liquid crystals before it is hardened, a seal-hole material should be especially free of contaminants.

(4) *Excellent printing and drawing capacity*

Sealant must be compatible with the orientation film. Sealant should lend itself to detailed printing and drawing so that patterns created using sealant can completely cover the large number of electrodes and interconnections. Usually, sealant patterns are created $1.5\text{--}10\mu\text{m}$ thick and $0.5\text{--}2\text{mm}$ wide, subject to variation from one LCD panel to another. It is necessary that patterns can be drawn easily, using either screen-printing or dispensers.

3.10 COLOR FILTERS

3.10.1 Structure of Color Filters

Figure 3.69 shows the basic configuration of a color filter. In this configuration, a glass substrate is coated with a $\sim 0.1\mu\text{m}$ thick opaque film, called black matrix (BM), and patterns are established in this film. The BM prevents any light leakage between adjacent pixels and protects the TFT from stray light. RGB color materials are provided at open

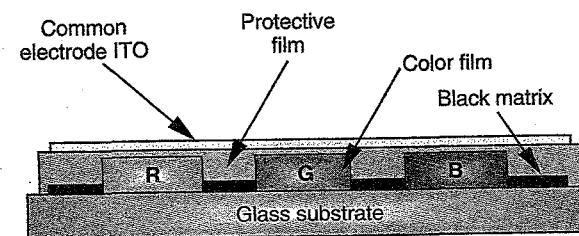


Figure 3.69 Structure of a color filter

areas that are not covered by the BM, i.e., those spots that form pixels. As a general rule, the color material film has a thickness of $1.2\mu\text{m}$ for any of the RGB colors. In the next step, a color filter protection film is deposited. The protective film also helps to make the filter surface flat by reducing the step difference between the RGB and the BM. And finally, a common electrode ITO film is deposited. The light transmission of RGB color filters relative to white light is approximately 25%.

RGB elements are arranged in stripe, mosaic, or delta (triangle) arrays (Figure 3.70). The type of array to be used is dictated by the particular color LCD to be produced. For enhanced picture quality, high-density products use stripe

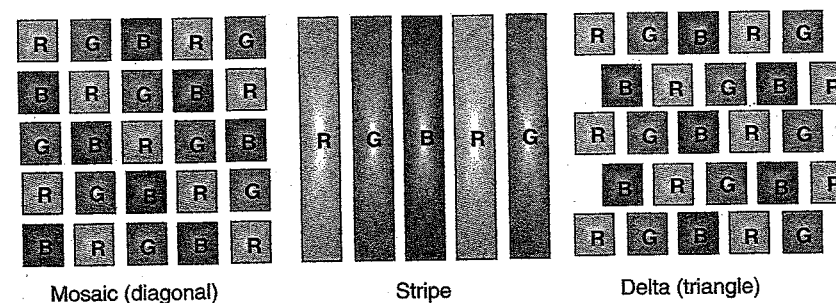


Figure 3.70 Color filter arrays

arrays, whereas low-density displays favor delta arrays. Generally, stripe arrays are used in computer displays, such as PC screens, while mosaic and delta arrays are used in 5-inch and smaller TV screens.

3.10.2 Black Matrix

The black matrix performs three functions: improving contrast, keeping color materials from becoming mixed, and shielding the a-Si film of the TFT from stray light.

To improve contrast, the screen must become totally black when the liquid crystal operates and light is shut off. A black matrix is used to prevent light leakage between pixels. The black matrix is used to fill the space between RGB elements on a color filter. Space between the different color materials prevents mixing of the colors. The intrusion of light from the outside into the TFT's a-Si semiconductor film can cause current to flow and to increase the TFT's leakage current. The black matrix blocks the light from external sources and prevents this problem as well. The technique of transferring the black matrix to the TFT array substrate side has been a subject of recent research.

The principal method for the fabrication of black matrix involves depositing a film of chromium by sputtering (Figure 3.71). A common technique for reducing reflection is to use a double layer of metal chromium and chromium oxide. This technique involves patterning the sputtered film by photolithography. In recent developments, newer materials have been produced that can reduce the cost of the black matrix and that can minimize reflection from the black matrix. These materials include: black resin, in which carbon and titanium are diffused in

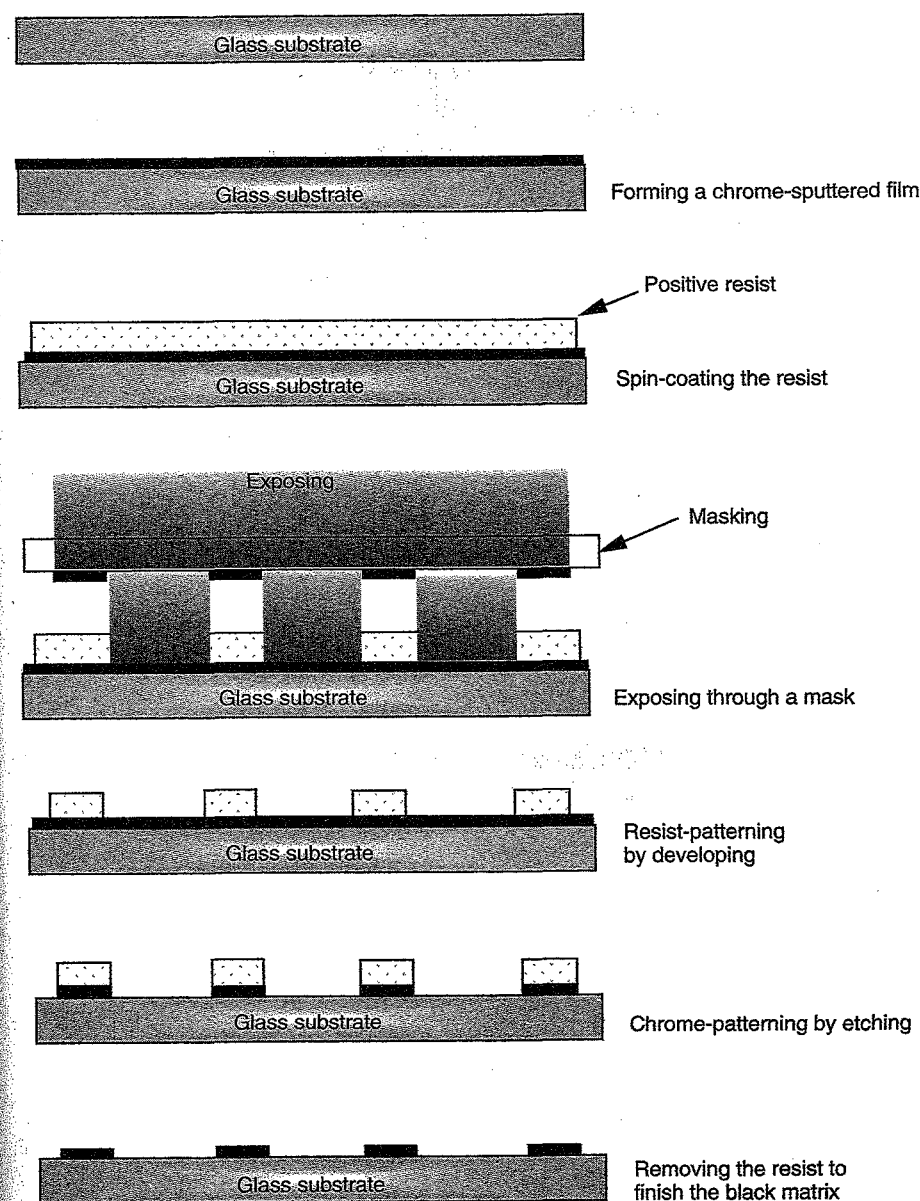


Figure 3.71 Fabrication of a black matrix

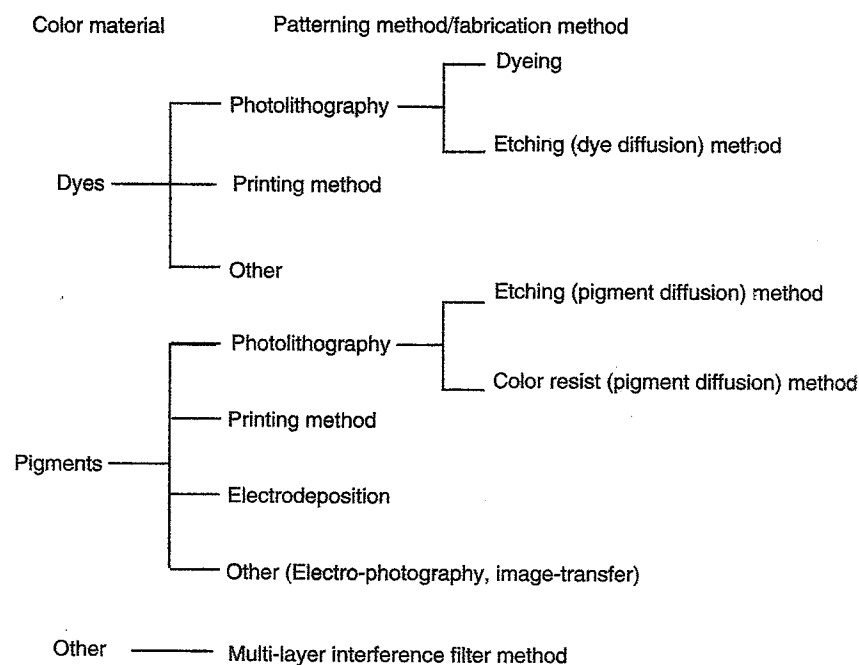


Figure 3.72 Classification of color filters

photoresist as a substitute for chromium, and metallic nickel material.

3.10.3 Types of Color Filters

Color filters can be divided into two major categories, based either on dyes or pigments. They can further be divided in terms of the coloring methods employed, such as dyeing, diffusion, electrodeposition, and printing. Figure 3.72 shows a classification of color filters.

3.10.4 Constructing a Color Filter

In this section, we present four leading methods for the

fabrication of color filters. No attempts will be made to treat methods that are currently under development such as micel electrolysis, electrodeposition-transfer, electro-photography, film diffusion, inkjet, and silver salt color emulsion.

(1) Pigment diffusion method

Depending on the types of materials used and the fabrication method employed, the pigment diffusion method can be divided into an etching method and a color resist method.

The etching method uses a colored resin, which is produced by diffusing pigments in polyimide resin. As shown in Figure 3.73, a colored polyimide-precursor liquid containing diffused red, R, pigments is spin-coated onto a glass substrate on which a black matrix has previously been formed. The coated glass substrate is dried and pre-heated. Positive resist is applied to the glass substrate, and then the glass substrate is mask-exposed. Then, an alkaline aqueous solution is used to develop the positive resist and to etch the colored resin film. An organic solvent is used to remove the positive resist. This forms a pattern of an R-colored resin film on the entire surface of the substrate. The same process is repeated for green, G-, and blue, B-colored resins. After a protective film is applied, an ITO film is deposited. The result is a finished color filter.

The color resist method uses a material called color resist as the colored resin, which is endowed with a photo-curing capacity. This eliminates the processes of positive-resist coating, development, and removal, which are required in the etching method. A color resist is made by diffusing pigments in a UV-curing resin (negative resist),

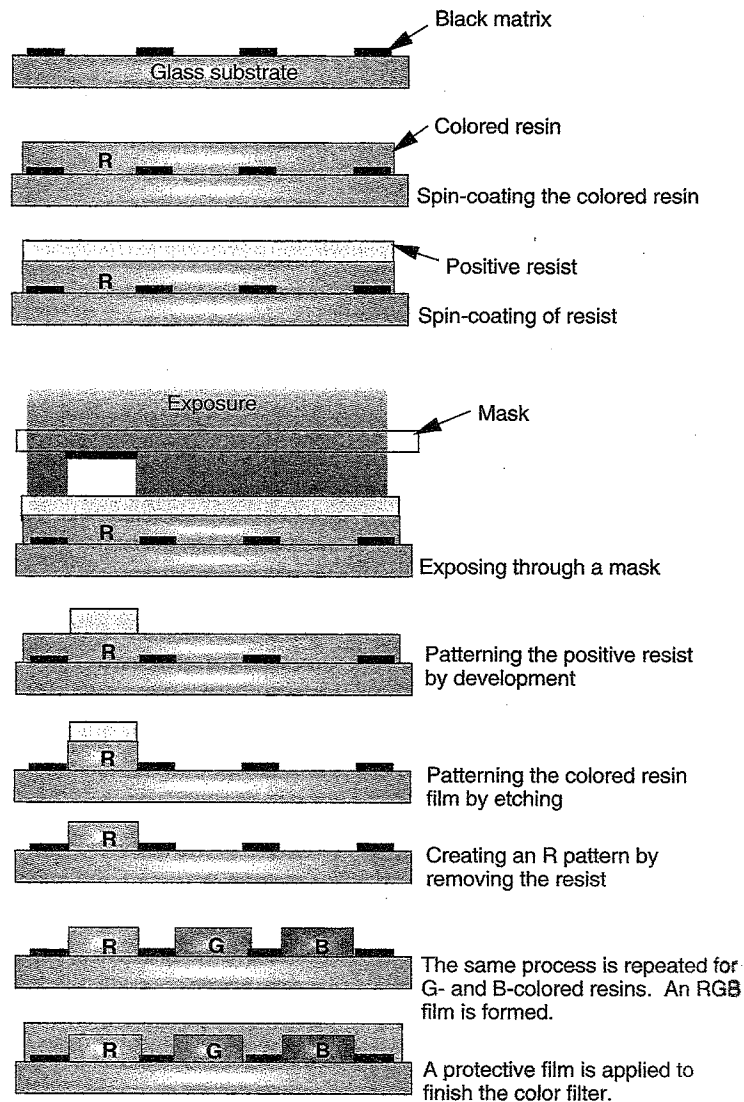


Figure 3.73 Making a color filter by the pigment diffusion (etching) method

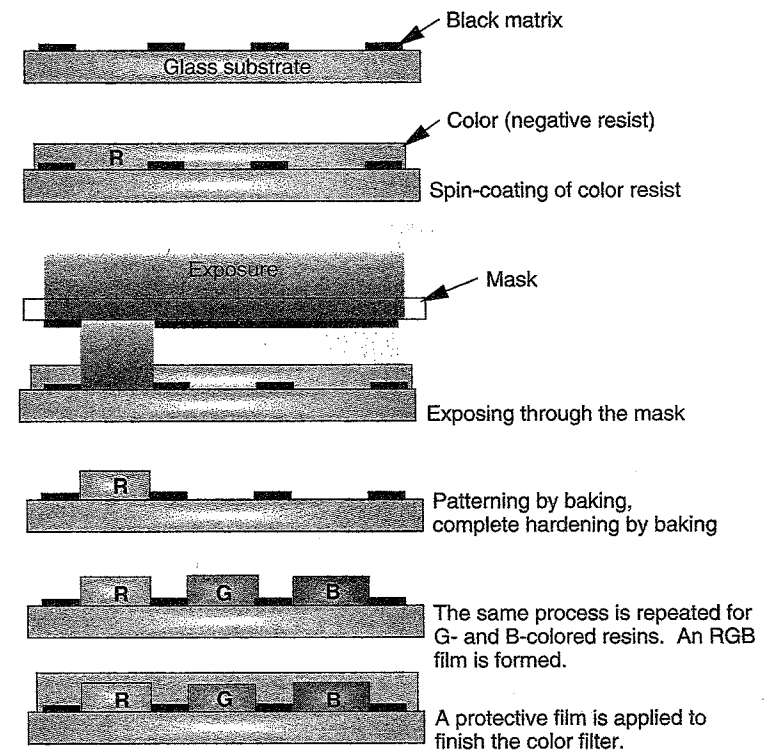


Figure 3.74 Making a color filter by the pigment diffusion (color resist) method

such as an acryl-epoxy resin, and dissolving the resin in a solvent. Figure 3.74 shows a color resist fabrication process. The parts of the color resist that were hardened by UV light during the mask-exposure process do not dissolve in the alkaline developer, and the parts that were not exposed to UV light readily dissolve the alkaline developer. Color resist materials that are actually in use include photo-bridging materials based on polyvinyl alcohol, and photo-polymerizing materials based on acryl resins.

Compared with the dyeing method, the pigment diffusion method offers greater environmental tolerance (ther-

mal stability), and is easier to process on an industrial scale. Most color filters are made by this method.

(2) Dyeing method

In the dyeing method, a glass substrate is coated with a photosensitive dye base (at this point, RGB colors are not yet applied), followed by the coating of positive resist. The positive resist is patterned by photolithography, and then is dyed in a red, R, color. The same process, beginning with the coating of positive resist, is repeated for G and B colors. The result is a finished color filter, as shown in Figure 3.75. The dyeing method offers a greater selection of dyes and facilitates the design of colors. Also, color filters made by this method possess superior spectral properties and transmittance. On the other hand, the method requires complex fabrication processes, and the organic materials used in this method are more vulnerable to the effects of heat or light than materials used in other methods. Polymeric and low-molecular-weight gelatin is used as a dye base in this method because of its superior overall properties, including transparency. The dyes used to dye the base material are either acidic or reactive dyes. Color filter fabrication methods using dyes include the photolithography dyeing method, (Figure 3.75) and the dye-diffusion (etching) method, which is similar to the pigment diffusion (etching) method.

(3) Electrodeposition method

The electrodeposition method involves dissolving an anionic resin in an electrolytic solvent, diffusing pigments, 0.15 μm in grain size, in the electrolytic solution, and electrochemically precipitating (electrodepositing) the anionic

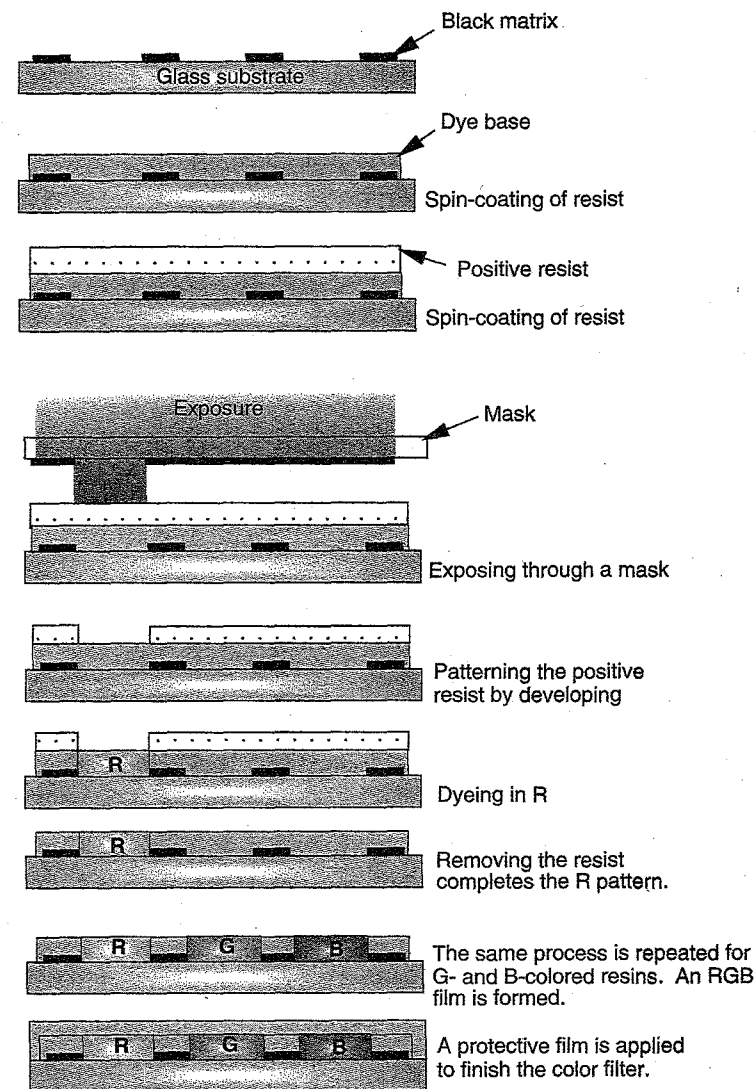


Figure 3.75 Making a color filter by the dyeing method

resin containing the pigments onto anodic ITO electrodes (Figure 3.76). The colored layer is baked after a color is electrodeposited. This method requires that the ITO film is patterned independently for each of the RGB colors.

Polyester and melamine resins are used as anionic resins because of their superior thermal stability, transparency, and resistance to bleaching. In the electrodeposi-

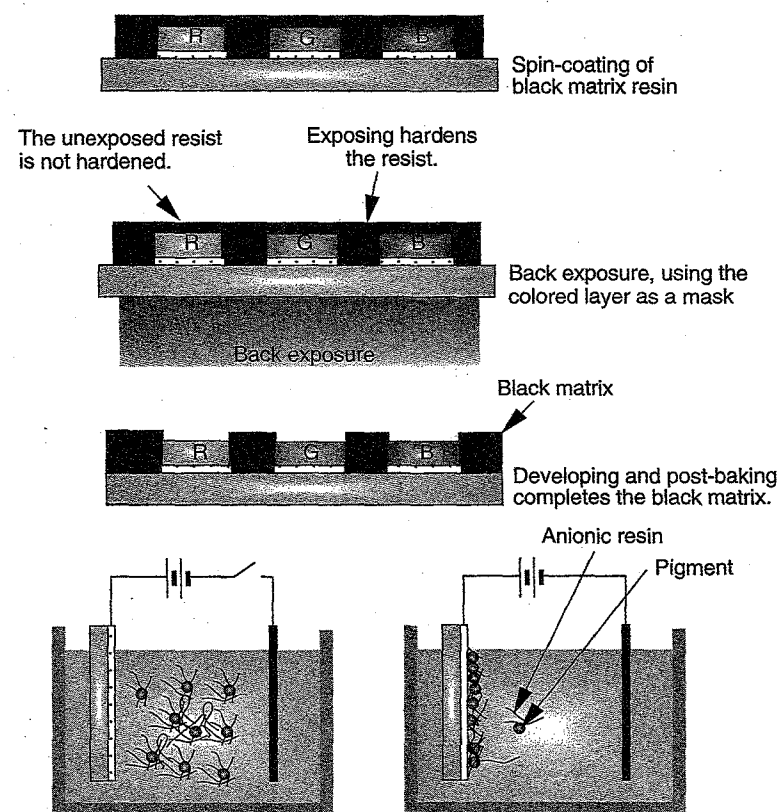
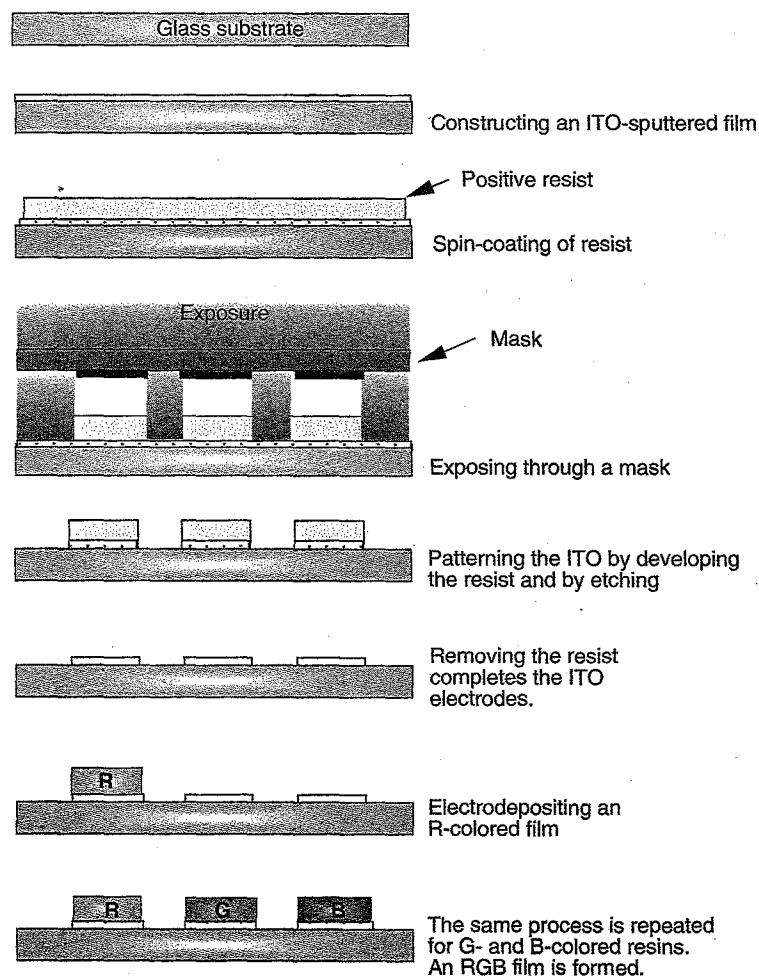


Figure 3.76 Making a color filter by the electrodeposition method

tion method, the thickness of the colored layer can be controlled by voltage and by electrodeposition time. Generally, electrodeposition is conducted for 20 seconds. Because the resistance of the ITO film itself can create uneven electrodeposition, a low-resistance ITO film must be used (less than $20 \Omega/\square$). Previously used for the fabrication of passive matrix LCDs, the electrodeposition method has made advances for the production of TFT color LCDs as well.

(4) Printing method

The printing method employs various techniques to print RGB inks onto a glass substrate (Figure 3.77). Representative techniques include: screen-printing, intaglio offset printing, planographic offset printing, relief flexo printing, and intaglio printing. Compared with other fabrication methods, the printing method is simple, is capable of forming a coating film and patterning simultaneously, offers a wide selection of environmentally tolerant materials, and is well suited to mass production. On the other hand, it presents technical difficulties, including the occurrence of uneven colors and a relatively low pattern precision. In the printing method, the common strategy

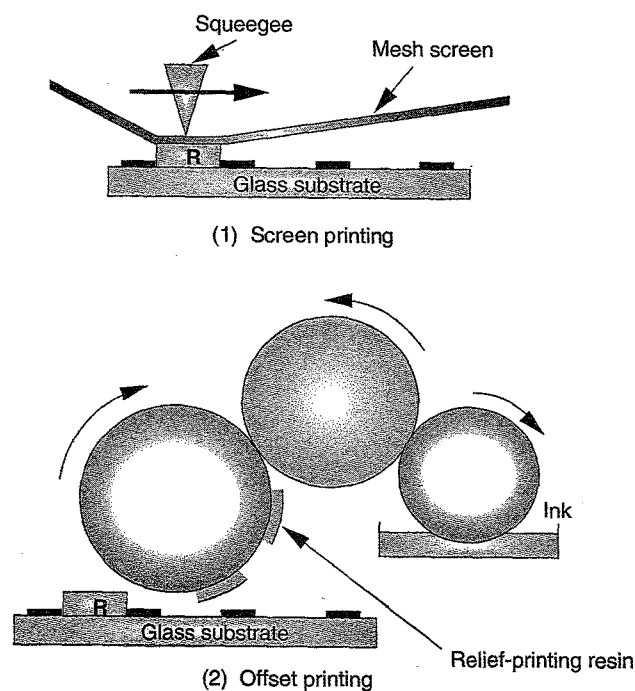


Figure 3.77 Making a color filter by the printing method

employed is to form black matrix by photolithography, and constructing colored layers by the printing method. This ensures adequate patterning precision. In some cases, the surface of the colored layer is polished in order to achieve complete flatness.

The ink used in the printing method is formulated with pigments, an ink base, and additives. Pigments are prepared by pulverizing either organic or inorganic pigments into sub-micron particles as diffusing agents. The following compounds are used as ink bases: oils such as oleic acid and stearic acid; solvents such as alcohols; monomers such as phenol and polyamide resin; and polymer oligomers. In addition, wax and plasticizers, such as varnish, are added. Drying promoters, viscosity adjusters, and bonding agents are also provided in the additive.

3.10.5 Properties of a Color Filter

The properties required of a color filter include the following:

(1) High color purity and light transmittance

A color filter must possess a high optical transmittance so that light does not attenuate as it passes through the filter. A color filter must also possess a high degree of color purity with good reproducibility for the colors that are produced by combinations of red (R), green (G), and blue (B). The rule of thumb is a color purity that approximates the primary color chromaticity coordinates for the color TV system defined by the National Television System Committee (NTSC). The colors produced by a color filter are matched to the emission spectra of the fluorescent backlight. A critical requirement is the absence of an overlapping of light transmittance spectra between filters of

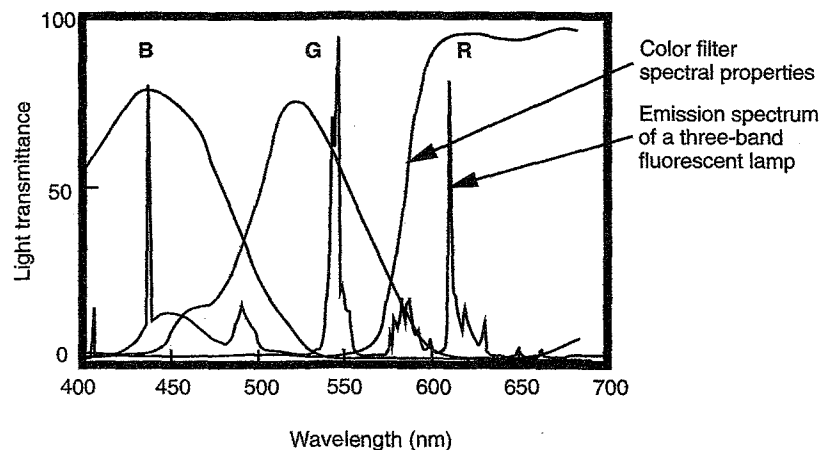


Figure 3.78 Color filter spectral properties

different colors. Figure 3.78 shows the emission spectra and the spectral properties of color filter elements and backlight.

(2) High degree of optical tolerance

Color filters should not undergo discoloration or fading due to the effects of backlight or when exposed to outdoor lighting conditions. Organic color materials are especially susceptible to discoloration. When used as a projection unit, a color LCD is subjected to a high luminous flux (on the order of a million lux at the color filter). This requires color filters that have superior thermal stability and resistance to bleaching. Color filters that resist bleaching, made by micell electrolysis, not requiring photoresist, have recently come into production.

(3) High thermal stability

This requirement relates to the color LCD fabrication process. Color filters should be resistant to heat so that there are no color-tone changes and no separation of color

material when the orientation film on the color filter is baked (e.g., at 180°C for one hour) or when a low-resistance ITO film is formed.

(4) Chemical resistance

Although a protective film is deposited in most cases, a color filter should not deteriorate due to the effects of solvents or cleaning liquids in the ITO electrode formation process or in the orientation film-coating process. In addition, there should not be any leaching of impurities from the color filter to the liquid crystal.

(5) Flatness

A color filter should not contain any foreign objects or surface bumps. This is a critical requirement because in STN the cell gap can significantly affect display quality.

(6) Dimensional precision

For attachment to a TFT array substrate, a color filter should have accurate physical dimensions. To meet stringent alignment precision requirements and larger aperture requirements, a color filter should be free of any pitch misalignment.

(7) High degree of assembly reliability

Color filters should possess a high degree of bonding to sealant. Even when the liquid crystal cell is used under high-temperature or high thermal impact conditions, the color filter should not change in physical appearance or in liquid crystal cell performance.

3.10.6 Comparison of Color Filter Types

Table 3.6 summarizes the properties of color filters.

TABLE 3.6 Color filter properties

PROPERTY	DYEING	PRINTING	PIGMENT DIFFUSION	ELECTRO DEPOSITION
Colored-layer resin	Casein, gelatin, polyimide	Epoxy	Acryl	Epoxy, acryl
Color material	Dye	Pigment	Pigment	Pigment
Color filter thickness (μm)	1 ~ 2.5	1 ~ 3.5	0.8 ~ 2	1.5 ~ 2.5
Spectral property	Good	Fair	Fair	Fair
Resolution (μm)	10 ~ 20	50 ~ 70	10 ~ 20	10 ~ 20
Surface flatness	Fair	Poor	Fair	Good
Thermal stability	180°C×1 hr	250°C×1 hr	260°C×1 hr	250°C×1 hr
Resistance to bleaching	Poor	Fair	Fair	Fair
Resistance to chemicals	Poor	Fair	Fair	Fair

Although the dyeing method excels in spectral properties, the pigment diffusion and electrodeposition methods produce superior thermal stability and resistance to bleaching. The dyeing and pigment diffusion methods are preferred from a density standpoint. The electrodeposition method is favored in terms of surface flatness. The printing method is the most economical method. Cost and properties remain the principal criteria by which these methods are judged.

3.11 POLARIZERS

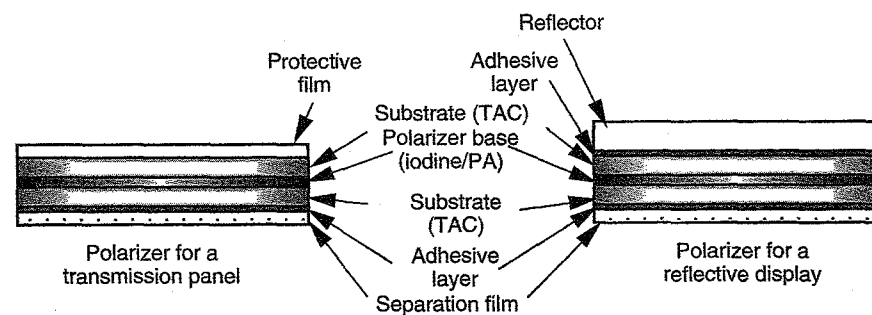
3.11.1 Need for Polarizers

A polarizer is made by placing a polyvinyl alcohol (PA) film, on which a dichroic substance such as an iodine complex is adsorbed, between rotating rollers, and then stretching the film 3 to 5 times its original length in one direction (uniaxial stretching) and orienting the iodine complex as well as the PA polymers. After iodine is adsorbed and

oriented, several films are attached to the polarizer film to provide protection. Variants of polarizers include those made by adsorbing iodine onto a polyvinyl butyral film, and dichroic-dye polarizers that contain dichroic dyes that excel in thermal stability and resistance to bleaching (acidic dyes, and especially azo-type direct dyes).

The configuration of the polarizer depends on whether the LCD for which the polarizer is intended is a transmissive display, a reflective display, or a semi-transmissive display. Figure 3.79 shows a cross-sectional diagram of polarizers. A polarizer is composed of a polarizer base (e.g., PA) containing polarizing elements (iodine or a dichroic dye), and two substrates that protect the polarizer base. A substrate is made from transparent triacetyl cellulose (TAC). An adhesive layer and a separation film are stacked on the polarizer base that contains the substrate. On the other side of the substrate, a protective film is attached to form a complete polarizer.

A reflective or a semi-transmissive polarizer employs aluminum foil, which is attached by means of an adhesive layer. The reflector can also be made by deposition of aluminum directly on the substrate. On the other side of the reflector, a

**Figure 3.79** Polarizer types and structures

separation film is attached to separate the adhesive layer. The separation film also protects the polarizer. When fashioned into a product, a polarizer has a thickness of 0.12 - 0.4 mm. Most color TFT displays use transmissive polarizers.

3.11.2 Properties of Polarizer Films for TFT Displays

(1) Excellent optical properties

Optical properties are especially important polarizer properties. Specifically, these properties include transmittance and the degree of polarization. The transmittance of a polarizer consists of the transmittance (T_1) of polarized light that is parallel to the direction of the polarizer's transmission axis, and the transmittance (T_2) of the polarized light that is perpendicular to the direction of the polarization axis. In a polarizer, these properties are adjusted so that T_1 is close to 1 (highly transparent) and T_2 is close to 0 (highly opaque). The transmittance of any single polarizer is expressed as the average of T_1 and T_2 . When two polarizers are used, their transmittance is expressed as the average of the sum of the squares of T_1 and T_2 when their polarization axes are parallel (parallel transmittance: T_{II}). When their polarization axes are perpendicular to each other, the transmittance of two polarizers is expressed as the product of T_1 and T_2 (orthogonal transmittance: T_I). In the case of a high degree of polarization, the parallel transmittance T_{II} can be approximated by two times the square of single-polarizer transmittance T . The degree of polarization P is an index of the polarization capacity of a polarizer, and this can be expressed as a function of T_1 and T_2 :

$$P = \sqrt{(T_1 - T_2) / (T_1 + T_2)} \quad (3.2)$$

Both transmittance and the degree of polarization should be as large as possible. Generally, polarizers have a single-polarizer transmittance of 38% - 48%, and a degree of polarization of 75% - 99.9%. For color display, the transmittance and the degree of polarization do not depend on the wavelength in the visible region. The polarizer must not be colored.

(2) Resistance to heat, humidity, and light

Here, we discuss only the resistance to the effects of heat and humidity. Iodine-based polarizers lose their polarization efficiency by the sublimation of iodine under high-temperature and humidity conditions. Therefore, efforts are under way to develop non-sublimating iodine complexes, to prevent the deterioration of PA due to intra- and intermolecular dehydration, and to optimize the cross-linkage and heat treatment operations that are performed in the polarizer fabrication process. The possibility of replacing triacetyl cellulose (TAC) substrate with a more humidity-resistant polyester (PET) and polycarbonate (PC) is also being investigated at research laboratories. Future expansion in the application of LCD displays requires further improvements in resistance to heat and humidity.

(3) Absence of defects that can degrade a polarizer's physical appearance or its transmittance

The film material (polarizer base) should be free of foreign objects and undissolved resin. The film surface should be free of any scratches. There should be no intrusion of foreign objects during the polarizer fabrication process.

(4) Surface treatment as necessary

To reduce surface reflection from the polarizer, the polarizer is provided with an anti-glare treatment, in which minute peaks and valleys are created on the surface; and an anti-reflection treatment, in which coatings of different refractive indexes are formed. Hard coating is also provided as necessary in order to prevent a build-up of static electricity and to make the film scratch-free.

3.12 DISPLAY BACKLIGHTING

3.12.1 Need for a Light Source

Displays can be divided into self-emitting displays and non-emitting displays. The CRT is a representative self-emitting device. The LCD is a non-emitting device, in which the liquid crystal regulates (modulates) the light transmittance. Since the LCD itself does not produce light, light must be obtained from an external source. In the reflective system, ambient light is used as is. The reflective system produces a display by reflecting ambient light from a highly reflective film (e.g., aluminum) that is fixed on the far side of the panel. In the transmissive system, a light source is provided at the rear of the LCD panel in order to supply illumination from the back. The light source used in a transmissive system is called a backlight. The displays used in personal computers and small TV sets are transmissive systems, especially in the case of color displays. These systems incorporate backlight units that are small fluorescent tubes with a special mechanism that transforms the point-source light beam emerging from the fluorescent tube into an area-wide illumination to cover the entire panel. Projection-type LCD displays require a

powerful light source in order to enlarge the image onto a screen.

3.12.2 Lighting a TFT Display

(1) Hot cathode fluorescent tube

Fluorescent tubes are the most widely used light sources because of their brightness, high emission efficiency, and color reproduction capability. In a fluorescent tube, the UV light that is emitted from the mercury that was excited by electric discharges strikes the fluorescent material that is coated on the glass tube wall. The fluorescent material converts the UV light into visible light. Three-band fluorescent lamps are usually used because of their ability to work in combination with color filters. Both hot and cold cathode fluorescent lamps exist. In a hot cathode fluorescent lamp, which operates in the same way as an ordinary fluorescent tube, a filament of a tungsten wire that is wound in a coil is coated with a substance that has a large coefficient of electron emission. (These substances, such as barium oxide and strontium oxide, are called emitters.) The life of a hot cathode fluorescent lamp is determined by the rate at which the emitter is consumed, since the emitter evaporates due to the evaporation of barium. Ways to prolong the life of a lamp include increasing the amount of the emitter and reducing the rate of consumption of the emitter. Compared with the cold cathode fluorescent lamp, a characteristic of the hot cathode fluorescent lamp is a high degree of brightness and high light-conversion efficiency. This is due to a high current density, and to a cathode voltage drop less than 14 V, resulting in low power consumption.

(2) Cold cathode fluorescent lamp

The cold cathode fluorescent lamp has the same basic structure as the hot cathode fluorescent lamp. The only difference lies in electrodes. In the cold cathode fluorescent lamp, electrons are released from the electrode not by the action of heat, but by a secondary electron emission. Nickel and tantalum are used as constituent materials in a cold cathode fluorescent lamp. In this lamp, electric discharges occur in both an ordinary glow region, in which the electrode voltage drop is independent of current, and in an extraordinary glow region, in which the electrode voltage drop has a positive characteristic. When the lamp is lit for a long period of time using the extraordinary glow region, the electrode substance accumulates on the lamp tube in mirror fashion. The cold cathode fluorescent lamp requires a higher start-up voltage, while producing a lower current density, light-emission efficiency, and brightness. On the other hand, it has a long life of 20,000 hours, it generates little heat, and thus it has less adverse impact on the liquid crystal. Both cold and hot cathode fluorescent lamps are now available in extremely small tube sizes (2 - 8 mm in external diameter). This has created increasingly slimmer backlight units, which have made significant inroads into direct-view color TFT LCDs that are used in personal computers.

(3) Diffusion electroluminescence (EL)

The EL backlight offers the advantage of generating an area-wide illumination, as opposed to point-source or linear illumination. The EL backlight used in LCD displays is an organic-diffusion device, in which an organic binder is used to diffuse copper-doped zinc sulfide and barium

titanate in ITO electrodes that are formed on a polyester film. While lightweight and slim, the EL backlight has low brightness and poor color rendition. In addition, it has a shorter life than the cold cathode fluorescent lamp (with attenuating brightness as a function of time) and it tends to generate noise. For these reasons, EL has largely given way to other technologies.

(4) Halogen and metal halide lamps

These lamps are used as light sources for projection TFT displays. Because of a point-source filament, the halogen lamp is well suited as a projection light source. With a stable color temperature of 3200K - 3400K, the halogen lamp produces a continuous spectrum and excels in color reproducibility. A short life of 50 to 500 hours due to a high filament temperature requires further improvement.

The metal halide lamp consists of a quartz glass tube containing a pair of electrodes with argon, mercury, and metal halide compounds (principally iodine compounds) that are sealed in the tube. The arc discharges between the electrodes produce white, stable light. The distance between electrodes is a small 5 - 7 mm. Metal halide lamps are widely used as projection light sources. They have a life of 2000 - 3000 hours, longer than a halogen lamp.

As indicated above, light sources for LCD displays require different properties according to the application for the display and the capabilities and size of the lamp to be used.

3.12.3 Edge Illumination

Hot and cold cathode fluorescent lamps are used in direct-view display backlights. Because they are linear light

sources, some mechanism is required so that the entire panel can be illuminated. The backlight unit performs this function, using either a top-down method or an edge illumination method.

(1) Top-down method

In this method, a fluorescent lamp is placed directly below the LCD panel. In this arrangement, the backlight unit has a structure in which one or more fluorescent lamps are set on a reflector and a light-control sheet and a light-dispersion sheet are placed above the fluorescent lamp (Figure 3.80). This system requires optimizing the position of the reflector according to the distance between the fluorescent lamp and the LCD panel surface, adjusting the thickness of the light-dispersion/transmission sheet, and controlling the dot patterns to minimize the transmittance of the light-control sheet above the fluorescent lamp. Drawbacks of the top-down structure include an increased backlight unit thickness, 1.5 to 2.5 times the diameter of the fluorescent lamp; and a non-uniform increase in LCD panel tempera-

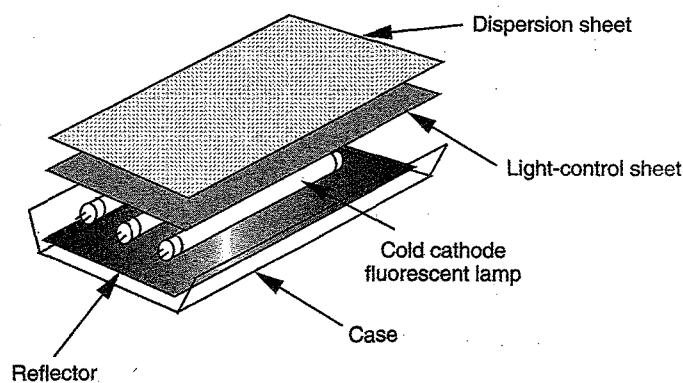


Figure 3.80 Top-down backlight unit

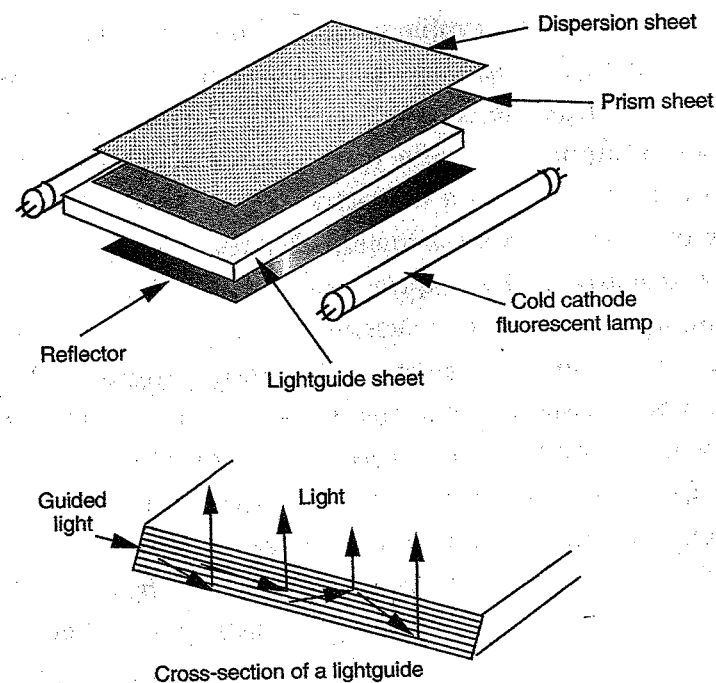


Figure 3.81 Edge illumination unit

ture due to the heating by the fluorescent lamp. The top-down method is used in automobiles and other applications where the premium is on brightness.

(2) Edge illumination system (lightguide method)

In the edge illumination system, fluorescent lamps are set at either one or two edges of a lightguide made from a transparent resin (Figure 3.81). A reflector provided on the back of the lightguide directs the light striking the lightguide to the surface of the LCD panel. A light dispersion sheet produces a uniform illumination. Because fluorescent lamps are placed on the sides, this method is also referred to as the side-illumination method. Its advantages are a

slimmer light source profile compared with the top-down method, and a low rate of heat propagation from the light source to the LCD panel.

The lightguide is made with an acryl resin, such as polymethylmethacrylate (refractive index = 1.49, critical angle of reflection: approximately 42°), because of its high light transmittance. For improving light utilization efficiency, the light-condensing unit for the fluorescent lamp should be optimized using a reflector, the edges of the lightguide unit should be treated for minimizing the reflection of light, and the reflector for the lightguide should be optimized. In some cases, in order to increase the brightness on the front side, an optical film called a prism sheet is added to the backlight unit. For improved light input onto the lightguide and for a reduced backlight thickness, the fluorescent lamp should be as small as possible. Therefore, cold cathode tubes of approximately 2 mm in diameter are used.

3.12.4 Properties of Backlights

Because they have a direct bearing on the performance of the display unit, backlight units are subject to stringent performance requirements as indicated below:

(1) High degree of brightness

To produce a screen brightness of 400 cd/m^2 , which is comparable to the brightness of a CRT, the required minimum backlight brightness levels are $2,700 \text{ cd/m}^2$ for monochrome displays and $13,000 \text{ cd/m}^2$ for color displays, given a liquid crystal transmittance of 15%-30% for monochrome units and 3%-6% for color units. Personal

computers require a color display brightness of 70 cd/m^2 , which translates into a backlight brightness of $1,500 - 2,000 \text{ cd/m}^2$. Side-illumination cold cathode fluorescent lamps typically have a tube-surface brightness of $30,000 \text{ cd/m}^2$.

(2) Uniform brightness

A minimum uniformity (minimum brightness divided by maximum brightness) of 0.8 is required. This value applies to the brightness range of $3.2 - 320 \text{ cd/m}^2$.

(3) High color temperature and reproducibility

Color temperature is a critical parameter for the display of a white color. A target value is one that approximates standard daylight illumination source D65 (color temperature: 6500 K). The spectral distribution of the light source should match the spectral transmittance of the color filter. As mentioned in the section on color filters, a wide color reproducibility range is required. To prevent the unintended mixing of colors, it is important that the backlight unit does not have emission peaks in the wavelength region in which the light transmittance of the colors (RGB) composing the color filter overlap.

(4) Low power consumption

Low power consumption is an important requirement for battery-operated, portable displays. The backlight unit accounts for most of the power consumption in an LCD unit. To reduce power consumption, improvements are needed in the emission efficiency of the fluorescent lamp, the light utilization efficiency of the lightguide, and the operating efficiencies of the fluorescent lamp and the drive circuits. In an LCD display for a notebook personal

computer, the backlight unit consumes 5 W, and the LCD panel drive circuits use 1.5 W, for a total of 6.5 W consumed.

(5) Low-temperature operation

A rule of thumb is that a backlight should be fully operational at -10°C (-30°C for automotive applications). At low ambient temperatures, fluorescent lamps tend to require a high voltage while producing less brightness. Although hot cathode fluorescent lamps perform better than cold cathode fluorescent lamps at low temperatures, cold cathode fluorescent lamps have been improved by replacing the radio-frequency switching with electronic switching and through the use of heaters. The cold cathode fluorescent lamps that use xenon instead of mercury perform well at low temperatures at the expense of a loss in brightness.

(6) Lightweight, slim configuration

In a notebook personal computer, the LCD module is about 15% of the total weight. Efforts are under way to make the lightguide thinner, without a loss in light utilization efficiency, and to reduce the diameter of fluorescent tubes to 2 mm. Weight reduction can be achieved by reducing the thickness of the glass substrate from 1.1 mm to 0.7 mm.

(7) Long life

The life of a hot cathode fluorescent lamp is about 3,000 hours for continuous operation and 30,000 on/off operations for intermittent use. Developmental efforts are continuing to achieve improvements in these parameters. The goals are 5,000 hours and 50,000 times, respectively. The cold cathode fluorescent lamp has an excellent life of 20,000 hours for continuous operation.

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