



Active Matrix Liquid Crystal Displays

Fundamentals and
Applications

Willem den Boer



Active Matrix Liquid Crystal Displays

Willem den Boer

Newnes is an imprint of Elsevier
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA
Linacre House, Jordan Hill, Oxford OX2 8DP, UK

Copyright © 2005, Elsevier Inc. All rights reserved.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of the publisher.

Permissions may be sought directly from Elsevier's Science & Technology Rights Department in Oxford, UK; phone: (+44) 1865 843830, fax: (+44) 1865 853333, e-mail: permissions@elsevier.co.uk. You may also complete your request on-line via the Elsevier homepage (<http://elsevier.com>), by selecting "Customer Support" and then "Obtaining Permissions."

Recognizing the importance of preserving what has been written, Elsevier prints its books on acid-free paper whenever possible.

Library of Congress Cataloging-in-Publication Data

Application submitted.

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

ISBN-10: 0-7506-7813-5

ISBN-13: 978-0-7506-7813-1

For information on all Newnes publications
visit our Web site at www.books.elsevier.com

05 06 07 08 09 10 10 9 8 7 6 5 4 3 2 1

Printed in the United States of America



AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Newnes is an imprint of Elsevier



Working together to grow
libraries in developing countries

www.elsevier.com | www.bookaid.org | www.sabre.org

ELSEVIER BOOK AID Sabre Foundation

The AMLCD manufacturers are supported by a large infrastructure of equipment and material suppliers, which continue to improve efficiency and reduce cost. They include color filter, polarizer, and optical film manufacturers, driver IC and controller IC vendors, packaging firms, backlight manufacturers, and suppliers of materials such as LC fluids and alignment layers.

The momentum the LCD industry has gained is difficult to supplant by alternative flat panel display technologies, even if, on paper, they may have advantages over LCDs.

1.2 Liquid Crystal Properties

After their discovery by Reinitzer in 1888, liquid crystals were, for many decades, considered interesting only from an academic point of view. Liquid crystals are an intermediate phase between crystalline solids and isotropic liquids, and combine certain characteristic properties of the crystal structure with those of a deformable fluid. Display devices utilize both their fluidity and the anisotropy associated with their crystalline character. The anisotropy causes the dielectric constant and refractive index of the LC fluid to depend on the orientation of its molecules.

Nematic liquid crystals are commercially the most interesting type. Upon heating, most crystalline solids undergo a phase transition to an isotropic liquid. The nematic intermediate phase (mesophase) occurs in certain, mostly organic, substances in a temperature range between the solid and isotropic liquid state. Figure 1.3 shows an example of the molecular structure of a liquid crystal, p-methoxybenzylidene-p-n-butylaniline (MBBA), with its nematic temperature range.

The liquid crystal (LC) molecules are generally elongated in shape and have a length of around 2 nm. Because of their "cigar" shape they tend to line up more or less parallel to each other in the lowest energy state. The average orientation axis along the molecules is a unit vector $\mathbf{n}$, called the director. Nematic LC molecules are not polar, so there is no differentiation between $\mathbf{n}$ and $-\mathbf{n}$. The dielectric constant and refractive index of the LC is different along the director and perpendicular to the director, as shown in Fig. 1.4, giving rise to dielectric and optical anisotropy, respectively. The dielectric anisotropy

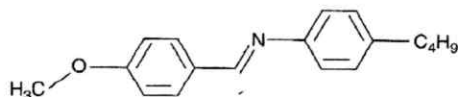


Figure 1.3: Example of molecular structure of LC - MBBA, with a nematic range of 21–48°C.

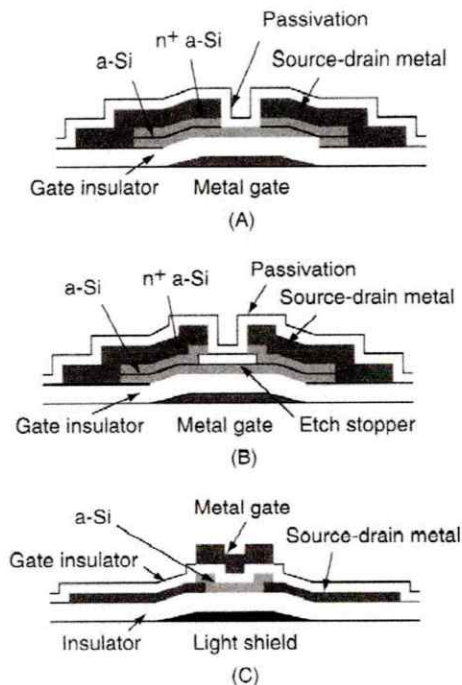


Figure 2.11: Three types of a-Si TFTs:
(A) back-channel-etched TFT, (B) etch-
stopper or trilayer TFT, and (C) top-gate
TFT.

maximize the ON current, and in the OFF state it blocks the injection of holes into the intrinsic i-layer to minimize the leakage current. Since the n⁺ layer is conductive, it needs to be removed from the channel area to obtain a low OFF current. This is done by a back-etch after the source and drain electrodes are patterned—hence, the name back-channel-etched TFT. The back-etch process is quite critical and needs to be uniform across the entire manufacturing substrate. Since it is difficult to obtain significantly different etch rates for the a-Si n⁺ layer and the undoped intrinsic layer (i-layer), good process control is required to completely remove the n⁺ layer from the channel without etching through the i-layer.

In the trilayer or etch-stopper TFT (Fig. 2.11B), the n⁺ back-etch is less critical, since there is an extra silicon-nitride etch stopper layer on top of the channel. The etch stopper is deposited and patterned before the n⁺ contact layer. Amorphous silicon and silicon-nitride can be selectively etched in dry and wet etch systems. During the back-etch of the n⁺ layer there is much better etch selectivity possible against the silicon-nitride etch stopper layer, enhancing the process latitude. The trilayer TFT also has a

thinner i-layer, which can suppress photo-leakage currents in the TFT. The major drawback of the trilayer TFT is that it requires an extra deposition and patterning step.

The top-gate a-Si TFT (Fig. 2.11C) is less common. In this configuration the source and drain electrodes are deposited and patterned first, followed by the a-Si layer. The gate insulator (usually silicon-nitride) needs to be deposited on top of the a-Si layer, which usually leads to somewhat lower-performance TFTs in terms of ON current. To suppress photo-leakage currents, a light shield needs to be deposited and patterned prior to the actual TFT process. It is separated from the TFT by an extra insulator layer. The extra processing required for the light shield and the insulator make the top-gate TFT less attractive.

Amorphous silicon is not a very stable material and its structure can be modified by strong illumination or by injection of charge carriers. In addition, the interface between amorphous silicon and the gate insulator (e.g., silicon-nitride) can accumulate charge during operation of the TFT. As a result of this charge trapping, the threshold of the a-Si TFT can shift over time. This effect has been studied in detail, since it can have a bearing on the lifetime of a TFT LCD. The threshold shift versus time can be expressed by the following equation:

$$\Delta V_{th} = (V_g - V_{th}) * \left(\frac{t}{\tau}\right)^\beta, \quad (2.10)$$

where β and τ are constants that can depend on temperature and the quality of the a-Si and a-Si/SiN interface.

The measurement results of threshold shift in non-optimized a-Si TFTs are shown in Fig. 2.12.

Fortunately, the threshold shifts are of opposite polarity during the ON time and the OFF time of the a-Si TFT, so that partial cancellation of the threshold shift occurs. The TFT in an AMLCD functions as an ON/OFF switch to load the pixel data on the pixel capacitor. Therefore, some variation of the TFT threshold across the area is acceptable, as long as the drive scheme can accommodate the variation. It also helps that for a few microseconds after switching ON an a-Si TFT, a transient current occurs that is about 2× higher than the steady-state current. The bottom line is that a-Si TFT threshold shifts have been proven to be small enough to not affect the lifetime of well-designed AMLCDs for up to 50,000 hours.

2.6 Poly-Silicon TFTs

Poly-silicon TFTs (Fig. 2.13) can be subdivided into the high-temperature variety (built on quartz) and the low-temperature type (built on low-cost glass). High-temperature poly-Si TFTs are manufactured with a process that is very similar to semiconductor

3.3 Thin Film Properties

The thin layers in the active matrix array are either conductor, insulator (dielectric), or semiconductor films. Polymer films are sometimes used as well. The films must satisfy a number of electrical, optical, and mechanical requirements to be useful in LCDs. An additional requirement is the ability to efficiently deposit and pattern the layers at acceptable cost on glass substrates with excellent yield.

The conductor films may be subdivided in metal layers that are patterned as the TFT electrodes and addressing buslines, and in transparent conductors such as indium-tin oxide (ITO) that are delineated as the pixel electrodes.

For the metal conductors, refractory metals (e.g., Cr, Ta, and Mo) were originally used. Although adequate for small displays, their resistivity ρ is too high for large displays exceeding about 15 in. in size. Table 3.3 lists the resistivities of some conductor films used in AMLCDs, along with their functions.

In thin films the resistivity is generally higher than in bulk metal; the exact value depends on the deposition process and the resulting film stoichiometry, crystallinity, and purity. For larger displays, some of the key parameters are the busline resistances, which need to be low enough to minimize signal propagation delays and resulting distortions of address pulses. The resistance R of a busline of metal film is

$$R = \rho \frac{l}{wd}, \quad (3.1)$$

where l is the length of the busline, w its width, and d the thickness of the film.

A useful parameter is the sheet resistance, defined as

$$R_{sheet} = \frac{\rho}{d}. \quad (3.2)$$

Table 3.3: Resistivities of thin film materials used in AMLCDs

Material	Function	Resistivity ($\mu\Omega\text{cm}$)
Ta	Gate electrode, select busline	20–200
Cr	Gate electrode, select busline	20
Mo	Source/drain electrode, data busline	13
Al	Both electrode, both buslines	4
Cu	Gate electrode, select busline	2.5
Al alloys	Gate electrode, select busline	4–10
ITO	Pixel electrode	100–300

CHAPTER 6

Improvement of Image Quality in AMLCDs

Over the past 15 years, the performance of AMLCDs has dramatically improved. Depending on the requirements for a particular application, the characteristics described in the previous chapter have been optimized. They include power consumption for portable devices, viewing angle for desktop monitors and televisions, contrast ratio, brightness, color gamut, and video response times for LCD televisions. In Table 6.1 the importance of different performance characteristics is listed for various applications. For mobile applications such as notebooks, PDAs, cell phones, camcorders, and digital cameras, low power consumption is essential to prolong battery life.

For non-portable, large AMLCDs the viewing angle and response time tend to be more of a concern. Many efforts have gone into the development and commercialization of AMLCDs with application-specific optimization of the viewing characteristics. These improvements are described in this chapter.

6.1 Brightness Improvements

The brightness of transmissive LCDs depends to a large extent on the backlight intensity. The most straightforward way to increase display luminance is therefore to turn up the backlight or to design brighter backlights. The display luminance is then proportional to the backlight intensity and can reach more than 1000 cd/m². However, there are drawbacks to raising backlight luminance. First, it increases power consumption, which is undesirable (particularly for portable applications). Second, it may require a different construction of the backlight (for example, multiple lamps rather than single lamp edge lighting) and can also have a negative impact on backlight lifetime. Third, high backlight intensity can cause heating of the display beyond 40–50°C, where display image quality may start deteriorating. Alternatives to raising the backlight intensity are addressed in the following subsections.

Active Matrix Liquid Crystal Displays

Table 6.1: Importance of AMLCD characteristics for various applications

Parameter	Small mobile	Laptop	Desktop	Television
High brightness	x	x	Δ	o
Wide viewing angle	x	x	o	o
Wide color gamut	x	Δ	Δ	o
Fast video response time	Δ	Δ	Δ	o
Sunlight readability	o	Δ	x	Δ
Low power consumption	o	o	x	x
Low weight	o	o	x	x
Thin profile	o	o	Δ	Δ

o, very important; Δ, important; x, less important.

6.1.1 Increased Color Filter Transmission

Besides the backlight, the components of the assembly determine the final display luminance, as shown in the previous chapter in Fig. 5.5. The first polarizer transmits about 42% of the light. The black matrix opening on each pixel (the aperture ratio) is typically 40–70% and the color filters transmit about 25% of white light (averaged over the red, green, and blue filter). Other layers and the exit polarizer further reduce luminance so that total transmittance is only 5–10%. It is difficult to increase the transmittance of the polarizers or color filters without affecting contrast ratio or color saturation, respectively. There is a trade-off between color gamut and brightness. By reducing the density of color pigments in the color filter materials, their transmittance at fixed thickness can be increased. This has an effect similar to reducing the thickness of the color filters: it increases the spectral width of the color filter and reduces color gamut and color saturation.

The trade-off is illustrated in Fig. 6.1, where the filter curves and chromaticity coordinates labeled 2 have twice the filter thickness or twice the pigment density as compared to those labeled 1. Thinner color filters are common in mobile phone displays where power consumption is more important than a wide color gamut. Since the color filter spectra become wider for thinner filters, display luminance improves at the expense of color purity. In Fig. 6.1B, the resulting color gamuts are schematically compared.

6.1.2 High-Aperture Ratio Designs

Efforts to improve AMLCD transmittance have focused on pixel aperture ratio. In conventional designs (Fig. 6.2A), the aperture is limited to less than about 55% because the

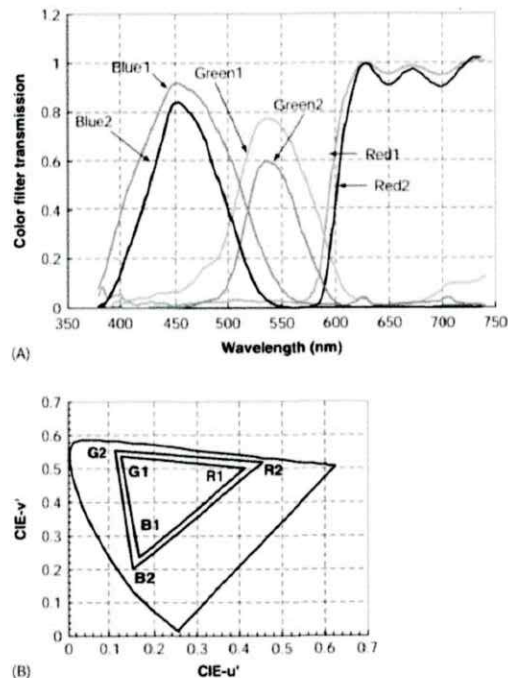


Figure 6.1: Effect of color filter thickness or pigment density on color filter spectra and color gamut.

black matrix on the color plate needs to overlap the ITO pixel electrodes on the TFT array by at least 4 or 5 μm . This is to allow for tolerance in the color-plate-to-active-plate alignment during manufacturing and to prevent light leakage at pixel edges.

In the black-matrix-on-array design of Fig. 6.2B, stripes of gate metal are added at the edge of the ITO pixel and determine the pixel opening. They block light entering the edge of the pixel under an angle. Since the registration of the layers on the TFT array to each other is very accurate (better than 1 μm), this makes a larger aperture of around 65% possible.

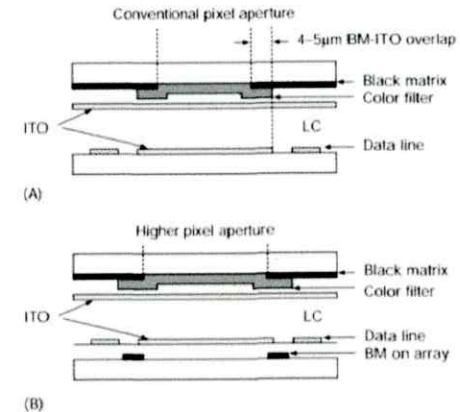


Figure 6.2: Pixel opening in conventional and in black-matrix-on-array designs.

In super-high-aperture designs (Fig. 6.3), the ITO pixel electrode overlaps the data and select buslines so that the buslines effectively function as the black matrix [1]. This leads to an even higher aperture of up to 80%. A thick polymer interlevel dielectric is used in super-high-aperture designs to passivate the TFT array. The ITO pixel electrode is patterned on top of the transparent polymer and makes contact to the TFT and the storage capacitor through vias in the polymer. The polymer is quite thick (2–3 μm) and has a relatively low dielectric constant of 2.7–3.5 to minimize the capacitance between the overlapping pixel electrode and buslines, required to keep vertical cross-talk in check.

The polymer has the added benefit of planarizing the TFT array surface and minimizing the LC disclinations at pixel edges, discussed in Chapter 5, Sec. 5.7. In principle, the black matrix becomes redundant and can be left out. However, this would expose the light-sensitive channel of the a-Si TFT to ambient light and would also cause the ambient light to reflect off the metal buslines, increasing display reflectance. An opaque, low-reflectance black matrix layer on the color plate is therefore still needed above the TFT channel as a light shield to prevent photo-leakage currents in the TFT and to minimize display reflectance. In a super-high-aperture design, however, the pixel opening in the black matrix can be much larger, as shown in Fig. 6.4. Obviously, the aperture ratio also depends strongly on the design rules and the pixel size. For larger pixels and more aggressive design rules, it tends to increase.

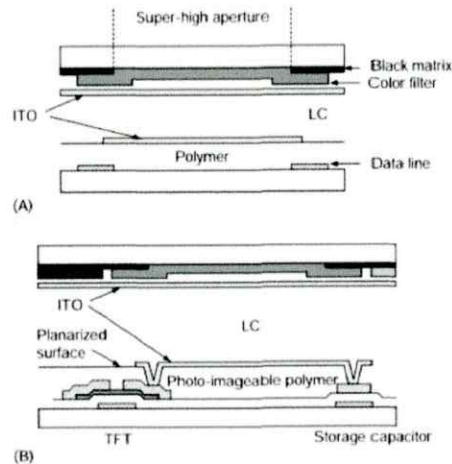


Figure 6.3: Cross section of super-high-aperture pixel through the data buslines (A) and through TFT and storage capacitor (B).

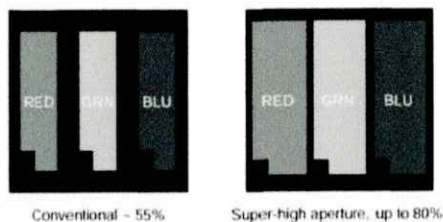


Figure 6.4: Comparison of aperture ratios in conventional and super-high-aperture ratio pixel designs as observed on a close-up view of an AMLC.

High aperture is important for portable applications, allowing the backlight intensity to be lowered while maintaining display luminance. The reduced power consumption in the backlight extends battery life. Alternatively, a higher brightness can be achieved without an increase in power consumption when the backlight intensity remains constant.

The material for the polymer in super-high-aperture designs may be the same as that used for the color filters except that the color pigments are not present. For example, it can be a photodefinable clear acrylic. Like the color filters, it is photo-imageable (i.e., it does not need photoresist coating, developing, and stripping, but is in itself a resist material).

Expanding on this concept, it is logical to go one step farther by simply replacing the polymer dielectric with color filter materials on the TFT substrate. This is called the color-filter-on-array (COA) method; see Fig. 6.5.

By patterning the color filters on the TFT array, the highest possible aperture is achieved (Fig. 6.5). The transparent polymer is replaced by separately patterned red, green, and blue color filters in each subpixel [2]. In the COA method the top plate has only a blanket transparent ITO layer. If the color filters cover the TFT channel they can also block most of the ambient light, eliminating the need for a black matrix. Since the common ITO layer is not patterned, there is no longer any critical alignment between the two glass plates and aperture is maximized. For very large substrates in Generation 6 and 7 facilities, it is very difficult to maintain accurate overlay accuracy between the top plate and the TFT array plate for all displays on the substrate. The COA design eliminates this problem and has therefore been considered in these advanced facilities. The drawback of the COA method is that the manufacturing complexity of the active substrate is significantly increased with at least two extra deposition and patterning steps, which can have an impact on yield.

6.1.3 Alternative Color Filter Arrangements

There are other methods to increase brightness without turning up the backlight. One that has received a lot of attention is alternative color filter arrangements. For example,

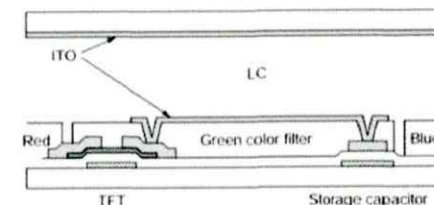


Figure 6.5: Cross section of a pixel in a COA (color-filter-on-array) TFT.