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Introduction
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1.1 INTRODUCTION

Flat panel displays (FPDs) have greatly changed our daily life and the way we work. Among several types of FPDs, the thin-film transistor (TFT) liquid crystal displays (TFT-LCDs) are presently the leading technology, with 30 years of manufacturing history. Recently, TFT-LCDs reached over 95% market share across TVs, computer monitors, tablet PCs, and smartphones, and are still expanding into other application areas.

The tremendous progress in TFT-LCD technology has brought us to the point where display performance, screen size, and cost far exceeded most industry leaders’ expectation projected at the time of initial TFT-LCD production, which started in the late 1980s. Owing to a sustained, enormous effort of display engineers around the world for the past three decades, the performance of TFT-LCD has not only surpassed the original leading cathode ray tube (CRT) in most areas, but also the cost barrier, initially considered to be prohibitive for mass adoption, has been reduced significantly by rapid advances in display manufacturing technology.

In this chapter, we briefly review the history and evolution of display technologies, focusing mainly on the manufacturing technology associated with TFT-LCD. With organic light emitting diode (OLED) displays in the form of mobile and TV becoming flexible, and growing and drawing a great deal of attention, the current status of active matrix driven OLED (AMOLED) display manufacturing technology is explored in sections 8A, 8B and 10.

1.2 HISTORIC REVIEW OF TFT-LCD MANUFACTURING TECHNOLOGY PROGRESS

Counted from the early stage production of TFT-LCD notebook panels that happened in the late 1980s, display manufacturing technologies have evolved enormously over the past three decades in order to meet the market demand for applications and different pixel technologies for notebook, desktop PC, LCD-TV, and mobile devices. The progress did not come easily, but it was the result of continued innovations and efforts of many engineers across the industry that enabled adoption of new technologies, process simplifications, and increased automation in order to achieve such economics of scale. In this section, we review the historic evolution in TFT-LCD manufacturing technology from notebooks to LCD-TV application.
1.2.1 Early Stage TFT and TFT-Based Displays

TFTs, more precisely, insulated-gate TFTs, have been critical enablers for the development of flat panel displays. Figure 1.1 shows a schematic cross-sectional view of the most common type of TFT device, a so-called inverted staggered TFT. In this device, there is a gate electrode on the bottom, which is covered with an insulator, followed by the active semiconductor material and a top passivation insulator. The passivation insulator is etched back to allow fabrication of source and drain contacts to the semiconductor.

P. K. Weimer at RCA reported first working TFT devices by using CdS as the semiconductor material in 1962 [1]. Various active materials have been developed in addition to CdS: CdSe, polysilicon, amorphous silicon (a-Si), and so on. Among these, a-Si remains presently the most widely used due to its practical advantages over other materials.

The first a-Si TFT was reported by LeComber et al. [2] in 1979, and considered a major milestone in TFT history from a practical standpoint. The characteristics of a-Si are well matched with the requirements of liquid crystal driving and provide uniform, reproducible film quality over large glass areas using plasma enhanced chemical deposition (PECVD).

The active matrix circuit incorporating a field-effect-transistor and a capacitor in every pixel element for LC display addressing, still widely used today, was first proposed by Lechner in 1971 [3]. Fisher et al. [4] reported on the design of an LC color TV panel in 1972. The first attempt for a TFT-LC panel was reported in 1973 by the Westinghouse group led by Brody [5], which demonstrated the switching of one row of pixels in a 6 × 6-inch 20 line-per-inch panel. In 1973 and 1974, the group reported on an operational TFT-EL (electroluminescence) [6] and a TFT-LC panel [7] respectively, all using CdSe as the semiconductor. In the early 1980s, there were active research activities working on a-Si and high temperature polycrystalline silicon TFTs. Work on amorphous and poly silicon was in its infancy in the late 1970s and nobody had succeeded in building a commercial active matrix display using these materials. In 1983, Suzuki et al. [8] reported a small-size LCD TV driven by a-Si TFT and Morozumi et al. [9] reported a pocket-size LCD TV driven by high-temperature poly Si. The 2.1inch 240 × 240 pixel LCD-TV introduced by Seiko Epson (Epson ET-10) is regarded as the first commercial active matrix LCD product. It prompted the Japanese companies to intensify their efforts to build large-screen color TFT-LCDs. In 1989, Sera et al. reported on the low-temperature poly Si (LTPS) process [10] by recrystallization of a-Si film using pulsed excimer laser.

1.2.2 The 1990s: Initiation of TFT-LCD Manufacturing and Incubation of TFT-LCD Products

In 1988, Sharp produced first 10.4-inch a-Si based TFT-LCD panels for notebook PC application, which launched the TFT-LCD manufacturing. In 1992, DTI (a company jointly owned by IBM Japan and Toshiba) introduced a 12.1-inch SVGA panel that was used for the first color laptop computer introduced by IBM (Figure 1.2).

Until that time, the product yield of 10.4-inch or 12.1-inch LCD panels stayed in a very low level, leading to very expensive panel prices. The industry was not yet fully convinced that the large-screen sized TFT-LCD panels could enter a mass production scale with a proper production yield and meet the cost criteria. Nonetheless, the demand of the full-color TFT-LCD portable laptop computer was very high despite its high price tag (the initial price of IBM CL-57SX was almost $10,000) and thus was able to accommodate the
unusual high price of notebook display panels (LCD panel cost was nearly 70\% of that of laptop computer), opening the door for the expansion of LCD mass production.

Triggered by the demonstration of high image quality large-screen 12.1-inch LCD panels, competition on larger LCD panels for laptop computers continued from 1994 to 1998. At the same period, determining an optimum mother glass size that can produce “future standard size” laptop screens was a critical issue in the LCD industry. Starting with 1995, three Korean big companies, Samsung, LG, and Hyundai, also entered the TFT-LCD business.

Figure 1.3 shows the landscape of LCD companies adopting different mother glass sizes to manufacture notebook display panels. The mainstream LCD panel size increased from 9.4 inches to 14.1 inches from 1993
to 1998, therefore, mother glass sizes increased accordingly from Gen 2 sizes (360 × 475 or 370 × 479 mm) to Gen 3.5 size (600 × 720 mm).

The panel size competition settled when NEC introduced 14.1-inch XGA panels in 1998. The expansion of TFT-LCD so rapidly progressed that it finally overturned the competitive super twisted nematic (STN) passive matrix LCD market in 1996, which has been used for a long time as the main display panel for laptop computers. This was possible due to the cost down effort and the superior resolution and color performance of TFT-LCD. Since then, between 1990 and 2010, the mother glass sizes of TFT-LCD plants have continuously increased to higher generation every two or three years.

Increasing the mother glass size is the most efficient way to reduce panel cost and meet the trend of increasing panel size. Furthermore, the LCD manufacturing technology progressed with numerous technology innovations such as reduced process steps and enhanced productivity with the introduction of new concepts for process equipment.

In the early 1990s, TFT-LCD panels were primarily used for notebook PC applications. In 1997, 15-inch diagonal panels were produced for initial LCD desktop monitor applications.

1.2.3 Late 1990s: Booming of LCD Desktop Monitor and Wide Viewing Angle Technologies

After TFT-LCD penetrated laptop computer screen by major portion reaching near 25 million units in 2000, the TFT-LCD industry had plans to enter the desktop monitor market, which at that time was 100% CRT. However, TFT-LCD was far behind in optical performance especially for viewing angle characteristics. In order to compete with CRT, which has a perfect viewing angle by its emissive display nature, viewing angle improvement became the most urgent requirement for the TFT-LCD industry before launching into the desktop monitor market. In that regard, wide viewing angle was no longer considered as a premium technology at that time, but was regarded as a standard feature.

In 1993, Hitachi announced the development of IPS (in plane switching) technology. In 1995, M. Ohta and a group at Hitachi built the first 13.3-inch color IPS panel [11]. IPS technology was commercially initiated by Hitachi and the technology demonstrated itself excellent viewing angle capabilities due to the nature of horizontal (in plane) movement of liquid crystal molecules with respect to the substrate plane. A few years later in 1998, Fujitsu announced the development of MVA (multi-domain vertical alignment) technology based on VA technology [12], in which building protrusion shapes on each pixel electrodes generates a fringe field for LC molecules and widens the viewing angle. However, the two technologies showed a large difference in device structure, process, and display panel characteristics. In order to establish a dominant market share over CRT monitors, a number of cost reduction features were rapidly pursued for incorporation into the production flow. In this regard, it was considered very important to ensure practical wide viewing technology that provides both a wide viewing performance as well as a high productivity. The alignment layer rubbing-less feature of VA resulted in key advantages for easiness in processing over larger mother glass, reduced a process step, and offered a wide process margin for screen uniformity. Throughout the LCD industry’s growth, IPS and VA technology groups historically competed with each other. This healthy competition promoted the progress of each technology. Owing to the rapid advance of wide viewing angle technologies, CRT monitor replacement has grown steadily since 1998. With the appearance of 17-inch and 18.1-inch LCD monitors equipped with PVA (patterned VA) and IPS technology, respectively, desktop monitor sales have doubled every year between 1998 and 2001 (Figure 1.4).

1.2.4 The 2000s: A Golden Time for LCD-TV Manufacturing Technology Advances

Followed by the rapid LCD desktop monitor market expansion, the LCD industry was knocking on the door of the TV market. However, in the late 1990s, the biggest mother glass size was Gen 4 sizes (730 × 920 mm) and the manufacturing technology for larger panel size was not ready at that time. In addition, color performance, contrast ratio, and motion picture quality of TFT-LCD were not sufficient for the LCD-TV application. Since then, intensive efforts were assembled in order to overcome these handicaps, with especially motion picture
quality being the most urgent item to be improved for target TV applications. From late 1990s to early 2000s, numerous new technologies for LCD TV were developed in the area of high transmittance, high contrast ratio, high color gamut panel fabrication, wide viewing angle technology, and motion picture enhancement technology. During this period, TFT-LCD technology as well as manufacturing technology advanced rapidly. This period was regarded as a golden time for LCD manufacturing that led the LCD technology to today’s mature technology.

In 2001, a prototype of a 40-inch HD grade (1280 × 768) TFT-LCD TV panel was introduced by Souk et al. [13] The panel demonstrated not only a size breakthrough at the time, but also it demonstrated a 76% NTSC color gamut, 12 msec response time, screen brightness 500nits, and PVA wide viewing angle technology that triggered the large-size TV market.

In 2005, the first Gen 7 size factory (1870 × 2250 mm) was built by Samsung Electronics and began to produce TV panels. One mother glass could produce 12 panels of 32 inches, 8 panels of 40 inches, or 6 panels of 46 inches as shown in Figure 1.5.

The flexibility to produce multiple display panel sizes from the available mother glass substrates initiated the full-scale production of LCD-TV followed by a rapid panel size increase from 40-inch to 42-inch, 46-inch, and 52-inch TV applications as shown in Figure 1.6.

The successful launching of Gen 7 size lines for large-size TV panels triggered the opening of the LCD-TV market. From the period of 2005 to 2010, the average TV panel size increased 2.5 inches every year. In October 2006, Sharp Corp. started the first Gen 8 size factory (2160 × 2460 mm), capable of producing 8 units of 52-inch LCD TV panels per glass. Through the rapid increases in volume production of LCD-TV panels, LCD-TV surpassed CRT TV volume in 2008 (Figure 1.7).

### 1.3 ANALYZING THE SUCCESS FACTORS IN LCD MANUFACTURING

The rapid growth of TFT-LCD market backed by the rapid reduction of panel cost was possible due to the fast LCD manufacturing technology progress. The advance of LCD manufacturing technology led to productivity enhancements and panel cost-down, that in turn contributed to the fast expansion of LCD market. The progress of LCD manufacturing technology was attributed to optimizing each individual process in the TFT-LCD process flow, as well as the advancement of process equipment and fab layout. The key factors that contributed to the rapid cost down were productivity enhancements by:

1. moving to larger mother glass size.
2. process simplification effort, such as four mask step TFT process and LC drop filling process.
3. efficient fab layout in conjunction with equipment technology advance that enabled higher throughput and reduced standby time.
**Figure 1.5** First Gen 7 size mother glass factory, allowing fabrication of 8 units of 40-inch TV panels per substrate (2005).

**Figure 1.6** LCD-TV panel sizes increase from 40 inches to 46 inches fabricated in Gen 7 lines.

**Figure 1.7** The volume of LCD-TV exceeded CRT TV in 2008.

Source: DisplaySearch 3Q’07 WW forecast
1.3 Analyzing the Success Factors in LCD Manufacturing

Fab layouts evolved from configurations based on process equipment using individual cassette transfer systems, to use of inline single glass substrate transfer systems to enhance glass transfer efficiency as shown in Figure 1.8.

The transition to larger mother glass sizes demonstrated to be the most effective way to reduce the panel cost. Figure 1.9 showed the average panel cost $20 per diagonal inch, which dropped to $10 per diagonal inch when the industry moved from Gen 4 size to Gen 5 size.

![Figure 1.8 Fab layout evolved to enhance glass handling efficiency, from transferring individual cassettes to the single glass substrate transfer system.](image)

![Figure 1.9 Average panel cost of $20 per diagonal inch dropped to $10 per diagonal inch when the industry moved from Gen 4 size to Gen 5 size.](image)

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1.3.1 Scaling the LCD Substrate Size

The initial mother glass size started with Gen 1 size (300×400 mm) in the mid-1980s, and was used as TFT-LCD pilot lines. Since then, the glass size evolved to Gen 2 size, Gen 3 size, Gen 4 size, and so on, as shown in Figure 1.10, with the largest to date reaching Gen 10 size (2880×3130 mm) at the factory built by Sharp Corp. in October 2009. The competition on the larger mother glass size doesn't seem to end here. BOE
Group is building its Gen 10.5 size LCD panel fabrication plant in Hefei, China. With the construction of the Hefei fab underway, which is scheduled for mass production in 2018, BOE will be capable of processing glass substrates that reach 3370 × 2940 mm. In addition to the construction of Gen 10.5 size fab, China Star Optoelectronics Technology (CSOT), a subsidiary of TCL Group, will kick off its construction project of the world’s largest Gen 11 size LCD panel fabrication plant in Shenzhen, China.

The productivity of LCD panels, measured by the number of display panels produced per mother glass, naturally increases as the mother glass size increases from Gen 3.5 size to Gen 8.5 size, as shown in Figure 1.11.

**Figure 1.10** TFT-LCD substrate sizes for each generation that increased from Gen 1 size to Gen 10 size (Source: AU Optronics Corp. 2012).

**Figure 1.11** Panel productivity and size increase as mother glass size evolves from Gen 3.5 size to Gen 7 size.
1.3.2 Major Milestones in TFT-LCD Manufacturing Technology

There have been numerous technology evolutions during the 30 years of TFT-LCD manufacturing history, from the late 1980s to the present, which can be found in every process step, materials, and equipment technology advances; these combined efforts contributed to make TFT-LCD the dominant flat panel display nowadays. Nonetheless, we select three most significant technology revolutions, based on the consideration that without these revolutionary technologies, TFT-LCD would not become a commodity product and the industry would not able to grow as much. These three selected technologies are:

1. AKT cluster PECVD tool
2. Wide viewing angle technology
3. Liquid crystal (LC) drop filling technology

1.3.2.1 First Revolution: AKT Cluster PECVD Tool in 1993

Scientists and engineers in CVD technology believed that a high vacuum process should be used for a-Si TFT fabrication in order to prevent ppm level contamination of oxygen and carbon in the films. The initial PECVD tools were the inline high vacuum system. The overall process time for depositing a-Si TFT took a long time and the PECVD process itself was regarded as a particle generation process. The cleaning of each chamber wall took nearly half a day. In early stage of TFT-LCD production, PECVD process was the most time consuming and troublesome process. In 1993, AKT introduced a new concept PECVD tool, equipped with mechanical pumps only without high vacuum pumps, fast glass handling cluster type chamber arrangement, and a convenient in situ chamber cleaning method. In situ chamber cleaning with NF₃ gas greatly reduced CVD film particle problem and maintenance time (Figure 1.12).

The appearance of this innovative concept tool significantly reduced the burden of a-Si TFT process.

1.3.2.2 Second Revolution: Wide Viewing Angle Technology in 1997

Throughout the LCD industry’s growth, wide viewing angle technologies, IPS and VA (Figure 1.13), contributed the most in replacing CRT monitors in desktop monitors and TVs. Without the wide viewing angle technology advance, the widespread adoption of LCDs would not happen.

Figure 1.12 Cluster type PECVD tool from AKT.

Figure 1.13 The structure of three wide viewing angle modes: IPS, MVA, and PVA.
1.3.2.3 Third Revolution: LC Drop Filling Technology in 2003

Before the invention of the liquid crystal drop fill method, the traditional liquid crystal filling process was vacuum filling process that has been used for a long time in the industry. This process was time consuming, by filling the liquid crystal into the cell gap of the assembled TFT and CF glass by capillary action. For example, the LC fill process itself took a few days for a 40-inch LCD panel in early stage of LCD-TV prototype in the early 2000s.

The appearance of LC drop filling technology, as well as the accurately measured amount of LC is dispensed onto a TFT panel directly (Figure 1.14), greatly reduced the bottleneck process and contributed significantly to the growth of LCD-TV market that started in 2003.

1.3.3 Major Stepping Stones Leading to the Success of Active Matrix Displays

Besides the abovementioned three technology revolutions, there were numerous major technology contributions that led to the success of TFT-LCD and AMOLED. We list other major stepping stone technologies that led to the success of active matrix displays [14].

- 1962 First working TFT using CdS, RCA
- 1971 Active matrix circuit, RCA
- 1974 First working TFT-LCD panel, Westinghouse
- 1976 First TFT-EL/TFT-LCD video panel, Westinghouse
- 1979 First working a-Si TFT, U of Dundee
- 1983 First working a-Si TFT-LCD, Toshiba
- 1983 First working poly-Si TFT-LCD, Seiko Epson
- 1984 9.5-inch 640 × 400 CdSe TFT-LCD, Panelvision
- 1988 First 9-inch a-Si color TFT-LCD for avionics applications, GE
- 1989 First 14.3-inch a-Si TFT-LCD for PC, IBM, Toshiba
- 1990 First large-scale Gen 1 TFT-LCD manufacturing, Sharp
- 1995 IPS, Hitachi
- 1997 14.1-inch notebook panel production, Samsung
- 1997 14-inch and 15-inch monitor TFT-LCD panel production
- 1998 MVA, Fujitsu
- 1999 First commercial AMOLED by Pioneer
- 2000 LED backlight, IBM Research
- 2001 40-inch TFT-LCD TV, Samsung
- 2003 First 52-inch TFT-LCD TV
- 2003 First color AMOLED product in camera, Kodak/Sanyo
- 2005 First 82-inch TFT-LCD TV
- 2006 First 102-inch TFT-LCD TV
- 2012 Large-area AMOLED TV panels, Samsung and LGD
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