Major Milestones in Liquid Crystal Display Development

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The earliest display of moving images was the motion picture projector, in which light from a bright lamp was passed through an image on a film that was then imaged onto a screen. In the 1920s and 1930s the first black and white television broadcasts were made and viewed on small black-and-white cathode ray tube displays. Such a display was achieved by writing a visible image on a phosphor screen with an electron beam. It required a vacuum tube and high voltage electronics, yet it produced a reasonable image. Over time cathode ray tube displays became larger and capable of color images. They also became very heavy, bulky, and power hungry, though they had good color rendition. However, they were all there were, and the industry developed color CRTs with screen sizes as large as 1 m in diagonal dimension. Alternative displays were tried such as plasma screens (an array of tiny, energy-hungry plasmas that excited special phosphors for each color that quickly were bleached by the UV in the plasma) or micro-mirror scanner displays. However, all of these were supplanted by the advent of the liquid crystal display, the LCD. Today these displays dominate the display marketplace due to their ability to be used in all sizes, from as small as a wristwatch to over 2.8-m-diagonal television screens. LCDs can be reflective, requiring just ambient light to be viewed, transmissive, requiring a backlight to enable viewing, or transreflective, in which a pixel is split into reflective and transmissive subpixels. In either case their advantages of light weight, lower energy demand, and scalability have won LCDs a dominant place in today's display marketplace. This essay explores how that happened.

Liquid crystal is a mesogenic phase existing between crystalline solid and isotropic liquid. In 1888, Austrian botanist Friedrich Reinitzer and German physicist Otto Lehmann discovered such an anisotropic liquid crystal. However, in the early days only a few compounds with a liquid crystal phase were available, and their melting points were quite high. Moreover, to utilize its large optical anisotropy the liquid crystal has to be aligned and an external field applied. Before the optically transparent and electrically conductive indium-tin-oxide (ITO) film was available, an alternative way to align a liquid crystal was by applying a magnetic field. Therefore, in the first few decades major research focused on magnetic-field-induced molecular reorientation effects. But the electromagnet required to align the liquid crystals was too bulky to be practically useful. Then in the 1930s Russian scientist V. Fréedericksz and colleagues started to investigate the electro-optic effects in nematic liquid crystals. Some basic concepts were formulated such as the Fréedericksz transition threshold and order parameter, which described the crystalline state of a liquid crystal. In the 1950s and 1960s, the dynamic behavior of a liquid crystal cell subjected to an external force, such as a magnetic field or electric field, was investigated by C. W. Oseen, F. C. Frank, J. L. Ericksen, and F. M. Leslie. These concepts and models provided the foundation for the rapid development of the useful electro-optic devices that followed.

In the 1960s, American scientists George Heilmeier, Richard Williams, and their colleagues at RCA (Radio Corporation of America) Labs developed the dynamic scattering mode and demonstrated the first LCD panel [1]. This opened a new era for electronic displays. Heilmeier was credited with the invention of the LCD. In 2006, he received the OSA Edwin H. Land Medal, and in 2009 he was inducted into the National Inventors Hall of

Fame. However, the dynamic scattering LCD, which utilized the electric-current-induced electrohydrodynamic effect, was intrinsically unstable. Also, its contrast ratio was poor and power consumption was high. As a result, it had a short life and was ultimately abandoned as a practical display technology.

In the 1970s, to overcome the instability, poor contrast ratio, and high operation voltage of the dynamic scattering mode display, Martin Schadt and Wolfgang Helfrich, and James Fergason independently, invented the twisted nematic (TN) effect and steered LCD in a new and productive direction. TN is regarded as a major invention of the twentieth century. In 1998, James Fergason was inducted into the National Inventors Hall of Fame. In 2008 Schadt, Helfrich, and Fergason received the IEEE Jun-Ichi Nishizawa medal in recognition of their outstanding contribution.

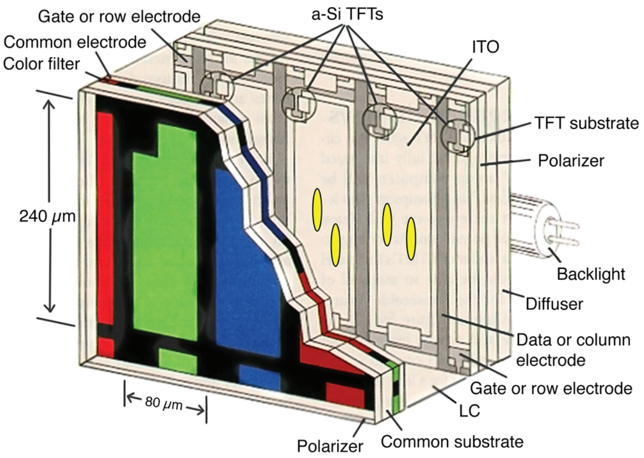
Also in the 1970s, a landmark equally important to TN was the development of stable liquid crystals called cyanobiphenyls by George Gray's group at Hull University [2]. Amazingly, these positive dielectric anisotropy ($\Delta\varepsilon \sim 15$) materials are still being used in some wristwatches and calculators in 2016. Meanwhile, to obtain a uniform domain new liquid crystal alignment techniques were developed. Among them, buffed polyimide deserves special mention because it enables large panel LCDs to be fabricated. This technique is still commonly used in modern LCD fabrication lines. Liquid crystals need a small pre-tilt angle (3°–5°) to guide their reorientation direction when activated by an electric field. Otherwise, different domains could be formed, which caused spatially inhomogeneous electro-optic behaviors. In addition to TN, vertical alignment (VA) and in-plane switching (IPS) were invented in the 1970s. In TN and VA cells, the electric field is in the longitudinal direction, while in an IPS cell the electric field is in the lateral direction, also called the fringing field. These three modes form the bases of modern LCD technologies. TN is used in notebook computers and personal TVs in some aircraft because of its low cost and high transmittance; multi-domain VA is widely used in high-definition TVs because of its unprecedented contrast ratio; and IPS is commonly used in mobile displays, such as iPhones and iPads, because of its robustness to external mechanical pressure allowing use in touch screens.

Another crucial development in the 1970s was the thin film transistor liquid crystal display (TFT LCD) led by Bernard Lechner at RCA and Peter Brody's group at Westinghouse. In 1972, a group at Westinghouse led by A. G. Fisher demonstrated that a color TV could be made by integrating red (R), green (G), and blue (B) spatial color filters with liquid crystal pixels as intensity modulators [3]. Each color pixel was independently controlled by a TFT. This combination of TFT and LCD enabled high information content and became the foundation of today's display industry. In 2011, three TFT pioneers—Bernard Lechner, Peter Brody, and Fang-Chen Luo—received the IEEE Jun-Ichi Nishizawa medal, and in 2012 Heilmeier, Helfrich, Schadt, and (the late) Brody received the prestigious National Academy of Engineering's Charles Stark Draper Prize to recognize their engineering development of LCD utilized in billions of consumer and professional devices.

The early TFTs developed by Brody and his colleagues were based on cadmium selenide (CdSe), which was never commercialized because of high off-current and reliability issues. Today, most LCDs use silicon TFTs: amorphous silicon for large panels [>10-in. (25 cm) diagonal], poly-silicon for small-to-medium panels such as iPhones/iPads, and single-crystal silicon for micro-displays. Recently, oxide semiconductors, e.g., $InGaZnO_2$ with mobility about 20× higher than that of amorphous silicon, have been attempted in TFT LCDs by major display producers. The high mobility of oxide semiconductors helps to shrink TFT feature size, which in turn leads to a larger aperture for higher backlight throughput.

In the 1980s, passive matrix and active matrix addressed LCDs were pursued in parallel. In the passive matrix camp, a new LC mode called super-twisted nematic (STN; twist angle >90°) was developed to steepen the voltage-dependent transmittance curve to increase information content. However, the viewing angle, contrast ratio, and response time of STN are far from satisfactory. In the active matrix camp, Seiko, Epson, and several Japanese display leaders invested heavily in active matrix TFT-LCD production facilities. In the meantime, new high-resistivity fluorinated liquid crystals were developed; this technology is required for active matrix operation to avoid image flickering. After nearly a decade of fierce competition, active matrix outperformed passive matrix and is commonly used in display products.

Figure 1 shows the device structure (one color pixel consisting of three RGB sub-pixels) of a TFT-LCD. LCD is a non-emissive display, so it requires a backlight or edge light, such as a cold cathode fluorescent lamp (CCFL) or a light-emitting-diode (LED) array. A thin liquid crystal layer is sandwiched between the active matrix substrate and color filter substrate, functioning as a spatial light modulator. Each sub-pixel is controlled by a TFT switch.



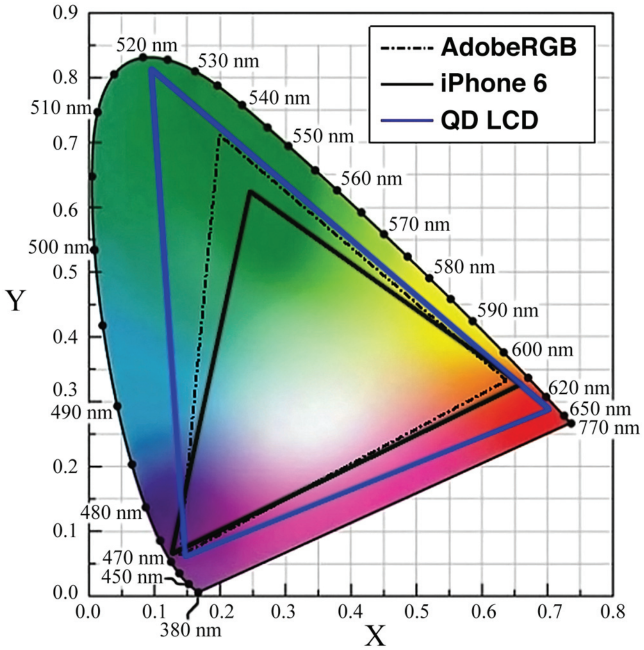
▲ **Fig. 1.** Device structure of a color pixel of thin-film-transistor LCD.

An important advancement in the 1990s was wide-view technology. Liquid crystal is a birefringent material, so its electro-optic property depends on the viewing direction. This problem gets worse as the panel size increases. To widen the viewing angle, two major approaches were undertaken: (1) multi-domain structure, e.g., four domains, and (2) phase-compensation films to reduce light leakage at oblique angles. To create four domains, zigzag electrode patterns were used. The viewer sees the average effect from four domains with size around 100 μm. Therefore, the viewing angle is widened dramatically. Once the viewing angle issue was overcome, there was a huge movement toward producing large-panel LCDs by Korean and Taiwanese manufacturers, in addition to those in Japan.

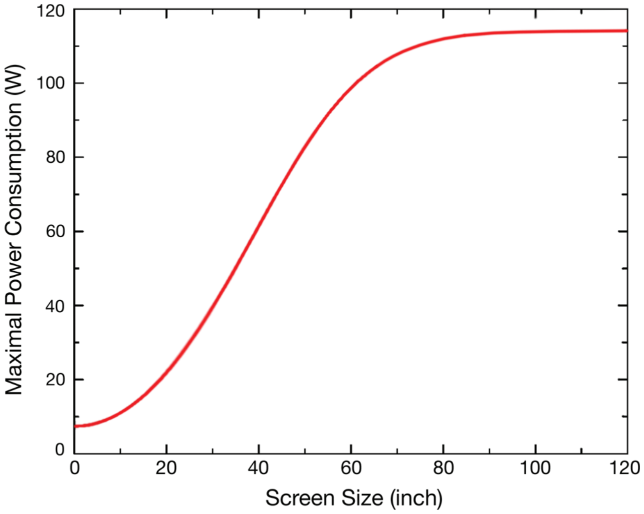
In the 2000s, in addition to large screen sizes and high resolution, LCD received two important enhancements: LED backlights and touch panels. The traditional backlight was a CCFL. It has a narrow green emission, but the red and blue are broad. As a result, some blue–green and yellow–red emissions leak through the corresponding blue and red color filters, so that the color gamut is limited to ~75%, similar to that of a CRT. To improve color saturation and reduce power consumption, two types of LED backlight were considered: white LEDs and RGB LEDs. White light can be generated by using a blue LED to excite yellow-emitting phosphors or combining RGB LEDs. The former approach is quite efficient, but its yellow emission is quite broad. Consequently, the color gamut is also limited to ~75%. The RGB approach greatly extends the color gamut to over 120%; however, it requires three driving circuits for the RGB LEDs. Moreover, there is a so-called "green gap" in the LED industry. That means there is limited choice for green LEDs in terms of color and efficacy. Both approaches were utilized by some major LCD developers, but eventually white LEDs won out. Nowadays, benefiting from progress in the general lighting industry, the efficacy of white LEDs has exceeded 100 lm/W. The touch-panel LCD was another important technological development in the 2000s. The Apple iPhone and iPad are examples of touch-panel LCDs. Numerous touch technologies were developed, including resistive, capacitive, surface acoustic wave, infrared, and optical.

In 2004, as a consequence of the rapid growth in the display industry, IEEE and OSA jointly launched a new journal, called the *Journal of Display Technology* (JDT). The author served as the founding editor-in-chief. The scope of JDT covers all aspects of display technologies, from understanding the basic science and engineering of devices, to device fabrication, system design, applications, and human factors.

In the 2010s, major research and development focused on faster response time, more vivid colors, higher resolution, larger panel sizes, curved displays, and lower power consumption. CRT is an impulse-type display; once the high-energy electrons bombard phosphors, the emitted light decays rapidly. Therefore, the displayed images do not remain at the viewer's eye, which means the images are clear. The only problem is that the frame rate should be fast enough (~120 Hz) to minimize image flickering. Unlike CRT, TFT-LCD is a holding-type display. Once the gate channel is open, the incoming data signals charge the capacitor and stay there until the next frame comes. Therefore, TFT-LCD is ideal for displaying static images, such as paintings. When displaying fast-moving objects, the



▲ **Fig. 2.** Simulated color gamut of the iPhone 6 and quantum-dot-enhanced LCD.



▲ **Fig. 3.** Maximum power consumption set by Energy Star 6. Aspect ratio: 16:9.

holding-type TFT LCD causes image blurs. To suppress image blurring, we can increase the frame rate, blink the backlight to make CRT-like impulses, and reduce the LC response time, which is governed by the visco-elastic coefficient of the LC material and the square of the cell gap. With continued improvement in developing low-viscosity LC materials and advanced manufacturing technology to control the cell gap at ~3 μm, the response time can be as small as ~4 ms.

Another issue for LCDs to overcome is color. Most LCDs use single-chip white LED backlighting: a blue InGaN LED to pump a yellow phosphor (cerium-doped yttrium aluminum garnet: Ce:YAG). This approach is efficient and cost effective, but its color gamut is ~75% and cannot faithfully reproduce the natural colors. Recently, quantum-dot (QD) LEDs are emerging as a new backlight source. Resulting from the quantum confinement effect, a QD LED exhibits high quantum efficiency, narrow-emission linewidth (~30 nm), and controllable emission peak wavelength. In comparison with conventional backlight solutions, QD backlight offers a wider color gamut. Figure 2 shows the simulated color gamut of the iPhone 6 (which uses white LED) and QD-enhanced LCD, whose color gamut is over 115% NTSC in CIE 1931 color space [4].

Power consumption affects the battery life of a mobile display and the electricity bill of a LCD TV. To be eco-friendly, Energy Star 6 sets the maximum power consumption for a given display size regardless of which technology is used. Figure 3 shows the maximum power consumption of a display panel with 16:9 aspect ratio. For example, the maximum power consumption of a 60-in. (1.52 m) diagonal HDTV (resolution 1920 × 1080) is ~100 W. As the resolution density keeps increasing, the TFT aperture ratio is reduced and power consumption is increased. To reduce power consumption, several approaches can be considered, such as a more efficient LED backlight, backlight recycling, a high-mobility oxide semiconductor to increase the TFT aperture ratio, and color sequential display to remove spatial color filters.

In the past five decades, we have witnessed the amazing progress of liquid crystal displays from concept proof to widespread applications. The technology trend is to go with a thinner profile, flexibility and bendability, lighter weight, more vivid color, lower power consumption, and lower cost.

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