The Evolution and Industry Impact of Consumer-Grade Display Technology

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Abstract. Display technologies have evolved significantly from the former cathode-ray tube (CRT) and liquid-crystal display (LCD) systems to the latest organic light-emitting diode (OLED) and micro light-emitting diode (micro-LCD). This paper categorizes these display technologies into two groups: traditional display technologies (CRT & LCD) and emerging display technologies (OLED and micro-LED), and analysis their respective structure, compositions, working principles and applications. CRT was once the major consumption of projectors because of its inherent advantages in motion rendering and color accuracy. However, limitations such as large size and low efficiency led to its eventual replacement by LCD technology. LCDs contains advantages of lower power consumption, thinner form and cost effectiveness, but has some shortcomings like slower response time and limited contrast ratios. The development of OLED resolved these shortcomings, though challenges related to cost, device lifetime and blue emitter degradation remain. Meanwhile, micro-LED shows potential in brightness, efficiency and durability. By reviewing these technologies, this work shows the balance between performance, cost and scalability, pointing out the solutions of next generation display.

Keywords: CRT, LCD, OLED, micro-LED.

1. Introduction

Nowadays, monitors and other display devices permeate every aspect of daily life. No matter the smartphone or pad, the television at home, the subway station indicator, even traffic lights are essentially display devices as well. It is widely used in industry, transportation, communications, education, aerospace, remote sensing satellite, entertainment and medical treatment. Display devices also can exist in several types, for example foldable screens, virtual reality/augmented reality headsets, projector, etc. In the consumer-grade market, OLED screens have become the dominant choice for almost all phones, while LCD screens are the most used in monitors.

The development of display devices traces back to the invention of CRT in 1897. For consumer-grade display technology, CRT technology was used for television and monitors. Its structure consists of an evacuated glass tube on one end and a display screen on the other end. An electron gun emits electron beams, whose trajectory to specific screen positions is controlled by a magnetic field changing the direction of screen locations. When these beams strike the phosphors on the screen, observable light energy was emitted by converting the electrons [1]. Due to several drawbacks of CRT technology, such as low refresh rates and large volume, it was replaced by LCD in 2000s. LCDs use the light-modulating properties of liquid crystals and polarizers to display. Nowadays, more display panels have emerged for monitors, including OLED, micro-LED and mini-LED. In brief, OLED, developed in 1960, is a type of LED that compounds an organic emissive electroluminescent layer, which is situated between two electrodes, and it contains at least one transparent electrode [2]. Micro-LED consists of arrays of microscopic LEDs arranged as individual pixel elements, which is first developed in 2000. It boasts lower energy consumption, offers pixel-level light control and higher contrast than LCDs. Compared to OLEDs, it also has a longer lifetime and low risk of screen burning in when displaying brighter images. Mini-LED combines LED and LCD technology. It shrinks LED modules as the backlight of LCD. This allows for more targeted and precise backlight control, while also can prevent backlight bleeding and enhance contrasts [3]. Up to now, most monitors still use LCD display technology rather than OLED and mini-LED. One of the majority reasons is that the cost of these new techs is still relatively high.

This article will categorize consumer-grade display technologies into two main categories: traditional display technologies which include CRT and LCD, and new pattern of display technology, which contains OLED and micro-LED.

2. Traditional Display Technologies

In brief, the antique and now popular used display technology is classified as the traditional one, which contains CRT and LCD. In this section will focus on the component, principle and application of CRT; it will also cover the history, principle and different panel types of LCD.

2.1. CRT

The CRT technology was first invented by Karl Ferdinand Braun in 1897. Then, in 1934, Telefunken made the world’s first commercial CRT electronic television sets, from when this technology started to blossom on the commercial field. The Core structure of the CRT is made up by three parts: a panel, a filter-liked funnel and a neck. The neck is made from a glass tube, while the other two components are shaped by pouring liquid glass into metal models. Meanwhile, due to these special art crafts, the material is also named CRT glass or television glass, which is designed to prevent electrons and X-rays. Inside the glass enclosure, there is an anode layer just in the front of the funnel. At the top sits a control grid containing a heater and a cathode. This part is called electron gun, which can emit electron beams. By controlling these electron beams, a graph can be shown on the phosphorescent screen [4]. The beams will shoot on the fluorescent screen to form a dot, and when the beams scan continuously, lines or complete images are generated. Most color devices have three electron beams, emitting red, green and blue color. By controlling the intensity of these three beams, a colorful image can be shown. Surrounding the glass core focuses on the coil rings and deflecting coils ring, to control focal distance and bent.

At that time, CRTs were the only devices to illustrate graph and display text. Instead of the letter split-flap display, CRT was a huge progress of display technology. From then on, commercial televisions and monitors all use this technology. In 1963, the world’s first consumer-grade color CRT came out. After wide range spread in mid 1990s, there are 160 million CRTs made per year, making them affordable by any family. Compared to the LCD, the progressive timing properties only exist on CRT, which means some games can only run on it. When these games were played on LCD displays, they cannot naturally blend the image and have higher input latency.

However, there are some drawbacks. For example, the volume of a CRT is too large, it requires much room to put a CRT, and due to the physical restriction, the screen size cannot exceed 45 inch [5].

2.2. LCD

LCDs uses the light-modulating properties of liquid crystals and polarizers to display. In 2000, they started to replace CRT displays, and in 2010, almost all the display devices have already change into LCD screen. An LCD is composed of a backlight, two polarizing filters, RGB color filter (CF) glass and cover glass [6]. The backlight passthrough the polarizer to change the natural light into polarized light. The liquid crystals then rotate the direction of this incident light by applying the voltage. At this sequence, the light remains white, so next step involves filtering the light into red, green and blue by the CF glass. A second polarizing filter cover on it, which is vertical to the first polarizer. In case of that, the light from backlight cannot passthrough these two polarizers without the interference of liquid crystal. By controlling the voltage applied on liquid crystal of each pixel, different amounts of light can pass through, thereby constituting different levels of grey.

There are three different panels of LCDs. The Twisted Nematic (TN) display is one of the oldest and cheapest liquid crystal technologies. It has fast pixel response times and less motion smearing than other panels. However, the color of TN is very unprecise. The view angle is very strict, even a slight shift of a few degrees will lead to the color shift. In-Plane Switching (IPS) is not the latest but the widely used. Their liquid crystals move horizontally in the layer instead of vertically moves, which reduces the scattering of light in the matrix, solving the poor color reproduction problem. Vertical Alignment (VA) has lower brightness and color reproduction in order to have better response, viewing angles and high contrast. Due to its vertical arrangement of liquid crystal, it can display black darker than other panels.

Mini-LED is not a standalone display technology but a type of backlight used in LCDs. Most LCDs uses a constant and uniform brightness backlight. Instead, mini-LED provides adjustable light to the backlight. It composes of thousands of mini-LEDs, which can open or close and change the brightness individually. This gives the ability to display dark black. Recently, a new type of mini-LED, RGB mini-LED is coming out. Instead of white LED light, it uses RGB light, and can preprocess the color of light before going to color filter. However, mini-LED is not a perfect technology. When facing a little light dot to display, noticeable halo will come out. The distinctness of halo depends on the brightness of backlight and the specific type of panels.

LCDs offer advantages such as lower bulk, less power and low heat emitting, along with high refresh rates (up to 600 Hz). CRTs have better color reproduction, reduce motion blur and no input delay. However, LCDs seem a little bit out of date due to their drawbacks, including low contrast ratio, low peak luminosity, high response time, and grayscale of screen.

3. New Display Technologies

This section will introduce more advanced and cutting-edge display technologies including OLED and micro-LED. They have extensive applications for newer electronic products.

3.1. OLED

OLED is a thin-film electroluminescent device that uses organic semiconductors to convert electrical energy into light. It was first invited by C. W. Tang and S. A. VanSlyke in 1987. Using a bilayer small-molecule structure, consisting of a hole-transport layer plus an Alq_3 emissive, electron-transport layer, the green light emission with high efficiency and low voltage was gotten [7]. It is the beginning of the development of modern OLED.

An OLED is typically composed of a stack of thin films. It is constructed by a transparent anode, commonly ITO, one or more organic layers that include hole/electron transport and emissive layers, and a cathode. When a bias voltage is applied, holes and electrons are injected from the opposite electrodes, migrate through the transport layers, and recombine in the emissive layer to form bound electron–hole pairs, which is called excitons. The radiative decay of singlet excitons produces fluorescence. Harnessing triplet excitons that go through phosphorescence or TADF enables much higher internal quantum efficiencies because roughly 75% of electrically generated excitons are triplets in spin-statistics-limited systems [8]. Key device metrics are external quantum efficiency (EQE), internal quantum efficiency (IQE), luminous efficacy (lm W^{-1}), color coordinates, and operational lifetime (e.g., T_{50} at a given luminance).

OLED devices employ three primary emissive strategies. First, fluorescent emitters. It is a singlet emission that uses simpler chemical compositions but limited to 25% IQE unless combined with additional strategies such as outcoupling or triplet harvesting. Second, Phosphorescent emitters. It is composed of heavy metal complexes, like Ir and Pt complexes. Phosphorescent emitters exploit strong spin-orbit coupling to use both singlet and triplet excitons, achieving near-unity IQE in some devices. A key study in the late 1990s showed that it is possible to achieve efficient phosphorescence [9]. Then, thermally activated delayed fluorescence, which is a more recent molecular strategy that enables reverse intersystem crossing from triplet to singlet states, allowing effective triplet harvesting without heavy metals. Materials families include small molecules and conjugated polymers. Each route has trade-offs: small molecules enable high purity and multilayer stacks; polymers favor low-cost roll-to-roll processing for large areas.

In terms of actual manufacturing, device stacks have evolved from single layer to multilayer architectures that separately optimize charge injection, transport, exciton confinement, and light extraction. Outcoupling is a major optical engineering challenge: due to waveguiding and substrate modes, a large fraction of internally generated photons can be trapped in the device, so strategies such as micro-lens arrays, high-index substrates, scattering layers, and internal outcoupling structures are essential to approach theoretical luminous efficacies. For white OLED lighting, device and optical design must balance color rendering, high efficacy, and device longevity [10].

Thanks to innovations in phosphorescent emitters and optical outcoupling technologies, OLEDs have reached high EQEs and practical luminous efficacy for displays. In some research demonstrations, lighting-level efficacy can compete with conventional technologies. Notable milestones include highly efficient green and red phosphorescent devices and white OLEDs with significantly improved lm W^{-1} via combined emitter and outcoupling engineering. However, device performance depends strongly on trade-offs between brightness, spectrum, and device lifetime.

Durability remains a major technical limitation for widespread OLED lighting adoption and for long-lived, high-brightness blue pixels in displays. Blue emitters, especially phosphorescent blue complexes, tend to degrade faster than green or red counterparts, causing color shift and reduced device lifetime. Degradation mechanisms include chemical instability of emissive molecules, formation of non-radiative traps, interface reactions, and morphological changes. As a result, research into accelerated aging protocols and lifetime-prediction methods remains an active research area.

OLED displays with thin-film transistor backplanes, have dominated premium smartphone and high-end television markets because of their high contrast, rapid response time and flexibility. However, manufacturing challenges include yield, encapsulation that is used to block oxygen and moisture, and the high cost of large-area uniform deposition. In the realm of lighting, large-area solution processing and lifetime improvements are central to commercial viability [11].

3.2. Micro-LED

Micro-LED, also written as μLED, is an emerging display technology that uses microscopic light-emitting diodes as individual pixels. This technology was first invented in 2000 by the research team led by Hongxing Jiang and Jingyu Lin at Kansas State University. They successfully demonstrated the operation of the earliest micro-LEDs, establishing the foundation for micro-LED display systems [12]. Unlike LCDs which require a backlight, and OLEDs which rely on organic emitters, micro-LEDs are inorganic, self-emissive semiconductors that directly generate light when an electric current passes through them.

Shrinking LEDs to micrometer scales increases perimeter-to-area ratio, exposing sidewall states created during Inductively Coupled Plasma (ICP) etching. These defects raise non-radiative Shockley-Read-Hall (SRH) recombination, shifting the peak External Quantum Efficiency (EQE) to higher current density and lowering maximum EQE. Foundational experiments and modeling on InGaN-based μLEDs established this trend [13].

To address these challenges, various surface treatments and passivation strategies have been developed. Chemical treatments like KOH, and dielectric passivation like Al_2O_3, HfO_2, via atomic-layer deposition (ALD) suppress leakage and surface recombination, recovering EQE and reducing size sensitivity. Multiple studies report significant EQE improvements and reduced extracted surface-recombination velocities with ALD. Notably, HfO_2 can outperform over SiO_2/Al_2O_3 on red AlGaInP-based μLEDs [14].

Beyond surface optimization, mass transfer and integration technologies are critical for scaling up micro-LED displays. Scaling to millions of pixels requires moving or forming μLEDs onto electronic backplanes with high accuracy and yield. Techniques include pick-and-place, fluidic, electrostatic, laser-lift/off-transfer, magnetic, and elastomeric stamp transfer printing, each balances throughput, placement accuracy, and damage risk. Among these, elastomeric micro-transfer printing—based on kinetically controlled adhesion switching --- remains a cornerstone technology and has been adapted for μLED arrays [15]. Industrial implementations demonstrate pixel “engines” that integrate μLEDs, interconnects, and micro-ICs before placement, pointing toward system-level yield management.

Regarding backplane and heterogeneous integration, complementary metal oxide semiconductor (CMOS) backplanes bonded to GaN epilayers have produced active-matrix μLED micro displays with resolutions ranging from hundreds to thousands of ppi, validating Au-free Cu/Sn bonding and post-bond substrate removal flows. Integration with oxide thin film transistor (TFT) is also advancing via improved bump metallurgy to raise yield and driving capability [16]

A promising alternative route is the low-temperature back end of line integration of atomically thin TFT matrices directly above LED emitters. This approach enables truly monolithic, vertically stacked devices with ultrahigh pixel density and low parasitic effects. A prototype reported in Nature integrates large-area MoS_2 TFTs with nitride μLEDs, achieving 1,270 ppi active-matrix operation and a luminance exceeding 7×10^7 cd/m^{-2} at low voltages, compelling for augmented reality (AR) micro displays [17].

In addition to performance and integration, device reliability is another crucial aspect for practical applications. Although μLEDs exhibit excellent intrinsic lifetime, display level reliability depends on three considerations. First, defect tolerance and yield management strategies, including repair mechanisms, pixel redundancy and binning. Second, the robustness of passivation, that is sidewall and metal. Then optical stack, such as micro-lenses, reflectors, crosstalk suppression for color-converted pixels. They maximize ambient contrast ratio and minimize light leakage. Quantitative ambience-contrast models are now being applied to guide quantum dot color conversion layer design for real-world viewing conditions [18].

For the application landscape of micro-LED, micro-LED technology is being developed for a wide range of fields. AR/VR micro displays require pixel densities above 3,000 ppi and brightness exceeding 5,000 nits, with even higher specifications for see-through AR systems. For compact optics, monolithic active-matrix (AM) approaches using CMOS or MoS_2-TFT back end of line are particularly attractive. Demonstrations above 1,200 ppi and even beyond 3,000 ppi AM arrays have been reported. Another major application is tiled video walls, or large TVs. Modular μLED tiles assemble into seamless walls with extreme brightness and longevity, while per-pixel driving circuitry improves uniformity and motion performance. The technology is also suitable for wearable devices, while high ambient contrast ratio and ruggedness enable sunlight-readable watch displays and automotive cluster. Although color-conversion stacks mitigate red-emitter gaps, ongoing research continues to advance native-red micro-LEDs.

4. Conclusion

This paper reviews the development of consumer-grade display technologies, tracing their evolution from early devices to emerging solutions. Chapter 2 introduces traditional display technologies, beginning with CRT, which states the foundation for electronic displays but is limited by its size. The discussion then proceeded to LCD, which replaces CRT with lighter structure, lower power consumption, and different panel types. Chapter 3 presents new display technologies. OLED has high contrast, fast response, and flexible design, though its cost and limited lifetime, especially of blue emitters, remain challenges. Micro-LED is recognized as a next-generation display, offering high brightness, long lifetime, and excellent efficiency, but still facing major obstacles in manufacturing, mass transfer, and cost.

Looking ahead, LCD is expected to maintain its dominance in monitors due to its affordability, while OLED is expected to continue to dominate premium smartphones and televisions. Meanwhile, micro-LED, though still in development stage, shows great potential for future applications in consumer devices, especially in AR/VR devices, wearables, and large-scale displays.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

[1] J. G. Hollands, H. A. Parker, S. McFadden, et al. LCD versus CRT Displays: A Comparison of Visual Search Performance for Colored Symbols. Human Factors: The Journal of the Human Factors and Ergonomics Society, 2002, 44 (2): 210-221.

[2] K. T. Kamtekar, A. P. Monkman, M. R. Bryce. Recent Advances in White Organic Light-Emitting Materials and Devices (WOLEDs). Advanced Materials. 2010, 22 (5): 572-582.

[3] T. Wu, C. W. Sher, Y. Lin, et al. Mini-LED and Micro-LED: Promising Candidates for the Next Generation Display Technology. Special Issue Group III-V Nitride Semiconductor Microcavities and Microemitters, 2018, 8 (9): 1557.

[4] T. R. H. Wheeler, M. G. Clark. CRT Technology. Widdel, H., Post, D.L. (eds) Color in Electronic Displays. Defense Research Series, 1992, 3: 221-256.

[5] O. Michitaka, K. Noboru, H. Koji, et al. A. Tetsuo. 1-2 Projection TV. Journal of the Television Society, 1993, 47 (7): 936-940.

[6] K. Hiroshi. The History of Liquid-Crystal Displays. Proceedings of the IEEE. 2002, 90 (4): 460-500.

[7] C. W. Tang; S. A. VanSlyke. Organic electroluminescent diodes. Applied Physics Letters. 1987, 51 (12): 913-915.

[8] Sebastian Reineke, Michael Thomschke, Björn Lüssem, et al. White organic light-emitting diodes: Status and perspective. Reviews of Modern Physics. 2013, 85 (3): 1245-1293.

[9] MA Baldo, DF O'Brien, YJ You, et al. Highly efficient phosphorescent emission from organic electroluminescent devices. Nature. 1998, 395: 151-154.

[10] Sebastian Reineke, Frank Lindner, Gregor Schwartz, et al. White organic light-emitting diodes with fluorescent tube efficiency. Nature. 2009, 459: 234-238.

[11] N. Thejo Kalyani, S.J. Dhoble. Organic light emitting diodes: Energy saving lighting technology—A review. ScienceDirect. 2012, 16 (5): 2696-2723.

[12] S. X. Jin, J. Li, J. Z. Li, et al. GaN microdisk light emitting diodes. Applied Physics Letters. 2000, 76 (5): 631-633.

[13] Pengfei Tian, Jonathan J. D. McKendry, Zheng Gong, et al. Size-dependent efficiency and efficiency droop of blue InGaN micro-light emitting diodes. Applied Physics Letters. 2012, 101 (23): 231110.

[14] Assan, Changmin Lee, Ryan Ley, et al. High efficiency of III-nitride micro-light-emitting diodes by sidewall passivation using atomic layer deposition. Optics Express. 2018, 26 (16): 21324-21331.

[15] Matthew A. Meitl, Zheng-Tao Zhu, Vipan Kumar, et al. Transfer printing by kinetic control of adhesion to an elastomeric stamp. Nature Materials. 2006, 5: 33-38.

[16] Xuehuang Tang, Xiaowei Huang, Taifu Lang, et al. Active-matrix TFT driven GaN blue Micro-LED display realized with electroplated copper-tin-silver micro bumps-based bonding structure. ScienceDirect. 2024, 1010: 177695.

[17] Wanqing Meng, Feifan Xu, Zhihao Yu, et al. Three-dimensional monolithic micro-LED display driven by atomically thin transistor matrix. Nature Nanotechnology. 2021, 16: 1231-1236.

[18] Liwen Deng, Xiang Zhang, Yinguo Yan, et al. Ambient contrast ratio of quantum-dot color-converted micro-LED displays. ScienceDirect. 2023, 48: 106462.