

Comparative Analysis of Next-Generation Flat-Panel Display Technologies

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Abstract. The rapid growth in the flat-panel display market has intensified the competition among three major electroluminescent technologies: light-emitting diodes (LED), organic light-emitting diodes (OLED), and quantum dot light-emitting diodes (QLED). This paper offers a comparison of these technologies on five dimensions (physical emission mechanism, colorimetric performance, reliability, manufacturing cost, and environmental sustainability). OLED leads in contrast ratio and mechanical flexibility because it emits light at the pixel level and can be fabricated on flexible substrates. QLED has the narrowest emission bandwidth (typically below 30 nm FWHM for CdSe-based quantum dots) and covers more than 90% of the Rec. 2020 color gamut. LED has clear advantages in peak brightness, with large-format installations regularly exceeding 5,000 nits, and it remains the most cost-effective technology at scale. Based on the research literature and the principles of semiconductor physics and colorimetry, this paper argues that no single technology excels in all areas. The paper also considers how EU RoHS regulation is restricting the use of cadmium-based quantum dots, creating future uncertainty for QLED manufacturers. Ultimately the main conclusion is that LED, OLED, and QLED will be in the mix for the foreseeable future and will be dominant in their respective application segments, and that a single technology is not able to achieve total market dominance.

Keywords: flat-panel display, OLED, QLED, LED, color gamut

1. Introduction

Display technology lies at the intersection of quantum physics, materials science, and consumer electronics. From the display of smartphones and laptops to the screens of surgical suites and digital cinema, the quality of visual output has a direct impact on how humans perceive, interpret, and act on information. The global flat-panel display market was valued at more than USD 150 billion in recent years and continues to grow; the demand for better resolution, wider color gamut and more energy efficiency across a wide range of form factors is increasing. Cathode-ray tube (CRT) technology was the dominant form of visual display for most of the twentieth century. The transition from LCD displays to LED backlighting started in the 2000s and took about two decades to complete; it is still happening in several sectors. The launch of OLED displays in the 2010s, which eliminate the backlight entirely and let each pixel create its own light, was a new paradigm. Quantum dot technology has recently provided a new kind of display, dubbed QLED. Such displays

leverage the size-tunable optical properties of nanoscale semiconductor crystals to produce color purity that conventional LEDs and organic emitters cannot easily achieve. The relative merits of these three technologies are based on their physical properties, their colorimetric properties according to the standard, as well as practical engineering and economic issues that dictate their use. In this paper, we attempt to compare them in a systematic, evidence-based manner. In this paper we discuss three interrelated issues. The first is to address the fundamental differences in physical emission mechanism, device architecture, and optical output of LED, OLED, and QLED technologies. The second is to address the application context where each technology has a structural advantage that is unique and how such claims can be justified. The third is to take into account the environmental regulations (the European Union's Restriction of Hazardous Substances (RoHS) Directive), which are relevant to QLED, and how this regulation will affect quantum dot displays in the long run. All of our conclusions are based on published literature and we do not provide experimental data. We analyze electroluminescent display technologies, distinguishing photoluminescent quantum dot films used in LCD backlights from true EL-QLED devices where relevant.

2. Physical and materials foundations

All three display technologies rely on the controlled emission of photons according to quantum mechanics. In spontaneous emission, an excited atom at energy level E_2 transitions to energy level E_1 , emitting a photon of frequency $\nu = (E_2 - E_1) / h$, where h is Planck's constant. The intensity of the emission is exponentially decreasing as $I(t) = I_0 e^{(-t/\tau)}$ where τ is the average excited state lifetime [1]. This is directly related to the aging behavior of organic and quantum dot emitters. The wavelength of the emission of a luminescent semiconductor is determined by the band gap, E_g . In an inorganic LED, when the p-n junction is forward-biased, electrons and holes recombine radiatively in the depletion region, emitting photons with energy $\approx E_g$. For a direct bandgap material like InGaN, this process is efficient as the threshold forward voltages are typically in the range of 1.4 V to 3 V depending on the wavelength [2]. Organic light-emitting diodes can be constructed with carbon-based molecular emitters embedded in thin films on a transparent substrate. The bottom of an OLED stack starts with an ITO anode and the hole-injection, hole-transport, emissive, electron-transport, and electron-injection layers are then followed by a reflective metal cathode [3]. Organic emitters produce fluorescence from singlet excitons and phosphorescence from triplet excitons. Fluorescence is produced from fluorescent devices which can capture at most 25% of the excitons. Quantum dots (QDs) are semiconductor nanocrystals, typically 2-10 nm in diameter, whose optical properties are determined by quantum confinement. Because the physical size of such nanocrystals is close to the de Broglie wavelength of the charge carriers, the effective band gap is size-dependent and smaller crystals emit at shorter wavelengths. This size-tunable emission allows a single material system like CdSe to cover the entire spectrum of visible light by controlling the diameter of the nanocrystal [4]. Cadmium-based II-VI QDs (e.g., CdSe/ZnS) have a photoluminescence quantum yield of close to 100% and emission FWHM less than 30 nm. However, cadmium is a dangerous substance under the EU RoHS Directive and is therefore not widely used commercially. Cadmium-free III-V QDs such as InP are being developed but still lag behind in terms of quantum yield and spectral purity. Device efficiency is defined by external quantum efficiency (EQE) as the ratio of photons emitted from the device surface to the number of electrons injected. EQE is lower than internal quantum efficiency due to optical losses from waveguiding, reflection, and absorption. Luminous efficacy is further related to the light emitted by the photopic luminosity function $\phi(\lambda)$

which peaks at 555 nm, and light-emitting devices primarily emitting in green achieve higher perceptual brightness than those emitting in the blue or red colors.

3. Colorimetric performance comparison

3.1. Colorimetry framework

The performance of colours is measured using the CIE 1931 XYZ color space and the xy chromaticity diagram in which all colors are located according to the spectral locus. The industry content standards — Rec. 709 for HDTV, DCI-P3 for digital cinema, and Rec. 2020 for ultra-HD — define reference gamut triangles that are of increasing size. Rec. 2020 covers approximately 75.8% of the visible gamut area and is the benchmark for next-generation displays.

3.2. Emission bandwidth and color purity

The main difference in the colorimetric characteristics between LED, OLED, and QLED is in the spectral quality of the emission. A conventional white LED for display backlighting is usually composed of a blue InGaN LED chip covered with a broadband yellow phosphor. The resulting white light has a continuous spectrum with a full width at half maximum (FWHM) of more than 100 nm for the yellow part. When this light is filtered through the color filters of a liquid crystal display to produce red, green, and blue subpixels, the broad spectrum means that each color filter outputs a relatively wide band of light. This shifts the effective chromaticity coordinates of each primary further away from the spectral locus and limits the achievable spectrum. OLED emitters have shorter spectra than phosphor-converted LEDs, with typical FWHM in the range of 50-80 nm for the individual RGB emitters. This improves color purity compared to LCD panels with white LED backlights and is one reason why OLED displays generally show more vivid colors. However, OLED emission spectra are still broader than the monochromatic ideal. Quantum dot emitters can achieve FWHM in the range of 20-30 nm. In a study directly comparing electroluminescent quantum dot devices with OLED devices, Dai et al. show that QD-LEDs based on CdSe/ZnS quantum dots have FWHMs of about 25 nm for green emission, while the reference green OLED has an FWHM above 60 nm [5]. Because the QLED emission spectrum is narrower, the primary color coordinates are closer to the spectral locus on the CIE diagram and can therefore cover a wider gamut.

3.3. Color gamut coverage

The relationship between emission linewidth and gamut coverage has been examined in detail. Brovelli and Klimov showed that a display using quantum dot primaries with FWHM below 30 nm could theoretically cover more than 90% of the Rec. 2020 gamut, compared to about 70% for OLED primaries with FWHM around 60 nm [6]. These figures show a clear hierarchy: QLED achieves the widest gamut, followed by OLED, with phosphor-converted LED exhibiting the least efficiency. This matters for the commercial market because Rec. 2020 compliance is increasingly important for premium televisions and professional monitors. The reduced spectral overlap between adjacent color filter channels in LCD subpixel designs also reduces crosstalk and improves saturation, even at moderate cost levels. The gamut advantage of QLED is applicable not only to high-end EL-QLED devices but also to the current generation of photoluminescent QD-enhanced LCD displays.

3.4. Human perception and subjective image quality

The photopic luminosity function $\phi(\lambda)$, which peaks at 555 nm, indicates that the human eye is more sensitive to green light than red or blue light of equal radiant power. A display device with luminance measured in nits (candela per square meter) is already implicitly weighted by $\phi(\lambda)$, since the candela is defined in terms of human visual response. A display that achieves high peak brightness mainly through a very bright green channel may perform well on luminance metrics but produce a perceptually unbalanced image. Thus, perceptual calibration of the three primary channels is important for high-quality color reproduction.

4. Device performance and engineering challenges

4.1. Luminous efficiency (EQE)

EL-QLED devices have exhibited impressive peak EQE values in laboratory settings for red and green emission, with green EQE significantly higher than 20%. However, the injection of electrons and holes into the quantum dot emissive layer to create excitons remains a challenging engineering problem. In the electroluminescent system, charge carriers must be injected from inorganic or organic transport layers into quantum dot nanocrystals with different surface chemistry, and interfacial carrier recombination and leakage lead to poor device efficiency. For cadmium-free InP-based QLED devices, both EQE and emission purity are still behind those of CdSe.

4.2. Contrast ratio and black level

Contrast ratio is the ratio of the brightest white to the darkest black a display can produce, and is one of the most important parameters of image quality. In a conventional LED-backlit LCD, the liquid crystal layer modulates the backlight by controlling the polarization state, but no LC cell can reach perfect light extinction. Due to the backlight leakage, the full-screen contrast ratio is approximately 1,000:1 to 5,000:1 in typical products. Local dimming, which uses many different backlight zones, can provide better contrast to certain parts of the image, but is also prone to halo artifacts around bright objects on a dark background. If direct emission EL-QLED displays existed, they would have the same structural advantage as OLEDs, i.e. they are controlled by individual pixels with full extinction capability. However, most commercial QLED televisions are backlit LCD panels with quantum dot color conversion films. They do not provide pixel-level light control and do not overcome the contrast problem with conventional LCD technology. Mini-LED backlights, which use thousands of smaller LED zones to enable finer local dimming, are an intermediate approach that partially addresses the problem, though the display remains a backlit LCD.

4.3. Peak brightness and outdoor readability

LED-based displays and backlights can reach very high peak luminance. Large outdoor LED installations are in the range of 5,000–10,000 nits. In consumer products, LED-backlit LCD phones and televisions with local dimming often reach peak brightness of 1,000–2,000 nits for sustained output and more for short highlights. This high brightness is vital for outdoor readability in direct sunlight, an area where LED technology currently has no equal. OLED displays are limited by the maximum current density that organic emitters can sustain without accelerating degradation. Sustained full-screen brightness is generally limited to a few hundred nits in consumer products, but short peak values for small high-brightness zones (for example, in HDR content) can reach 1,000–

2,000 nits in recent flagship panels. The biggest engineering trade-off in OLED is that the best sustainable brightness comes at the cost of accelerated aging.

4.4. Lifetime and aging

The lifetime of a display device is usually expressed as T50 or T95, which indicate the time after which the device decays to 50% or 95% of its initial luminance under certain driving conditions. LED backlights have a lifetime much longer than 50,000 hours even at moderate levels of brightness. OLED lifetime has improved greatly in the last 20 years, but blue organic emitters are still the most critical. Blue OLED materials degrade faster than red and green, so that the three primary channels in an RGB OLED display will diverge in intensity over time. This results in a characteristic shift in the color balance of the display and can be seen as a yellowish cast in panels that have been used for extended periods. The variety of pixel layout schemes (Diamond RGBG pattern of Samsung and BOE Blue Diamond) can be used to reduce the current density of each blue subpixel in comparison to the stripe layout. Flexible OLED technology has a great practical benefit. Organic thin films can be deposited on flexible polyimide (PI) substrates and the bottom layers consist of flexible barrier materials. Flexible OLED displays can be bent, rolled and folded. Flexible smartphones of many companies and curved and rollable TV panels are available in the market today. Flexible OLED technology allows for form factor advantages that cannot be obtained with a rigid glass substrate. Micro-LED represents a third pathway for high-performance display development. It is made up of arrays of microscale inorganic LED chips, and promises high brightness and longevity of LED, and pixel-level light control like OLED. The single biggest engineering barrier is mass transfer. The high-quality resolution of a full-resolution display is achieved by moving millions of individual LED chips, of less than 100 micrometers in size, with high positional accuracy and near-perfect yield. achieve the combination of high quality, high performance, and low cost needed for consumer displays, but efforts are being made.

4.5. Manufacturing process

OLED display manufacturing for smartphones and smaller panels requires vacuum thermal evaporation in the form of fine metal mask (FMM) templates to deposit the organic layers of each subpixel in patterned form. The precision of the FMM process limits the minimum pitch and thus the maximum pixels per inch (PPI) achievable without weakening color separation between subpixels. Sub-pixel rendering (SPR) algorithms that rearrange the subpixels in the display array (e.g., Pentile RGBG and Diamond RGBG) are used to achieve higher perceived resolution than the number of subpixels in the display array. For large OLED panels at television size and above, mask-based evaporation is not feasible; instead, white OLED with color filter (WOLED) or inkjet-printed OLED is used. Solution-based QLED manufacturing, such as inkjet printing, spin-coating or slot-die coating can be much less expensive than vacuum evaporation methods. The challenge is to achieve the film uniformity for consistent emission across large panel areas and production batches. Quantum dot ink formulation, substrate preparation and drying dynamics during printing are all processes under development. The simplicity of solution processing versus vacuum deposition is the reason why QLED is widely cited as a promising candidate for low-cost large-area displays, but this has not yet been commercially realized.

5. Cost, environmental impact, and sustainability

5.1. Raw materials and toxicity

All quantum dot materials are based on cadmium selenide (CdSe), often with a zinc sulfide (ZnS) shell to enhance quantum yield and minimize non-radiative surface recombination. Cadmium is a toxic heavy metal that is a probable human carcinogen, and its environmental accumulation and effects on aquatic organisms are serious concerns. Cadmium is not allowed to be used in electrical and electronic equipment as described in the EU Restriction of Hazardous Substances (RoHS) Directive. Although there are exemptions for small amounts of cadmium in quantum dot display applications, these exemptions are always reviewed and renewed. Thus, the regulatory landscape is highly uncertain for manufacturers looking to implement large scale production of cadmium-based quantum dots.

5.2. Manufacturing cost

OLED display manufacturing is costlier, especially for large displays. The vacuum evaporation equipment required for mask-based deposition of small molecule OLEDs is capital-intensive, and the use of expensive organic materials is inefficient because much of the evaporated material is deposited on surfaces other than the substrate. For Gen-8 glass substrates (2.2 m × 2.5 m) used for large TV panels, the quality of evaporation-based OLEDs has historically been lower than that of LCDs at comparable production volumes. LG's decision to produce large OLED TV panels using white OLED plus color filter approach instead of direct RGB evaporation shows the difficulty of achieving high yield with RGB mask evaporation on large substrates. LED-based products are able to reap decades of manufacturing efficiency over time. Standard LED backlights are made with mature epitaxial growth and phosphor conversion processes at a high yield and low per-unit cost. This cost advantage will persist even as OLED yields improve, because the materials and capital costs for organic deposition are structurally higher than for inorganic epitaxy.

5.3. Power consumption

OLED displays use more power as a function of the brightness of the image in the display because each pixel is only using electricity when it is emitting light. A predominantly dark image (a photo from the night or a user interface with dark mode enabled) will consume far less power in an OLED display than a backlit LCD display, which runs its backlight at nearly constant power no matter what content is displayed. This makes OLED more power-efficient in applications like smartphones, where an enormous amount of screen-on time is spent on moderately lit interfaces. LED-backlit LCD displays consume roughly the same amount of power regardless of image content. The backlight power is the most critical factor, and while local dimming can reduce it somewhat for low-average-picture-level content, the average power draw in OLED displays is high for dark images.

5.4. Life cycle assessment

A full environmental comparison of display technologies must take into account the entire product life cycle, from raw material extraction and processing through production and use, to end-of-life disposal. Manufacturing-phase impacts are generally larger for OLED and QLED than for LED because of the difficulty of deposition and the use of specialized materials. Operating energy consumption over a typical product life cycle of 7-10 years may favor OLED in mixed content

applications. At the end of life, cadmium-containing QLED products must be handled in a special way to prevent cadmium from being released into the waste stream, and cadmium-free alternatives eliminate this concern entirely.

5.5. Industry structure and patent landscape

OLED display supply chain is dominated by Samsung Display and LG Display for panel manufacture, while BOE Technology Group and other Chinese manufacturers are developing their own competing technologies. The production of advanced OLED panels in a small number of fabs introduces supply chain risks for device manufacturers that rely on external OLED panel supply. Samsung's QD-OLED technology uses quantum dot color conversion on top of blue OLED emissive layer instead of RGB OLED structure. This is a hybrid solution that leverages Samsung Display's existing OLED infrastructure and the color purity advantage of quantum dots. This product category, which was made available in 2022 and is in the mix with traditional WOLED and a future EL-QLED, shows how competition is driving a convergence between the two technologies. Micro-LED is being developed by Apple, Samsung, Sony and a number of startups and the patent environment is very controversial considering the strategic importance of the technology. Micro-LED products are available in the ultra-large format commercial signage space but they haven't reached consumer price points for televisions or smartphones.

6. Conclusion

In this study we evaluated three leading flat panel display technologies LED, OLED and QLED in terms of emission, color gamut, device life span and manufacturing cost, and environmental impact. We found that each of the three technologies is of different merits for different applications and that no single technology is superior in all dimensions. OLED leads in contrast ratio and device flexibility; QLED has the narrowest emission bandwidth and the widest color gamut; and LED has the best peak brightness and is most suitable for mass production. These findings support the idea that the three technologies are likely to be complementary rather than one replacing the others. Many previous studies focus on one or two aspects in isolation, while this paper attempts to understand the trade-offs across the full device and product life cycle. This study builds upon previous theoretical work and draws on colorimetric standards such as Rec. 2020 and CIE 1931; these standards help to provide a more accurate measure of the gamut claims in comparison with qualitative descriptions. It has practical relevance for engineers, product developers and policymakers in the display industry. The strengths and weaknesses of each of the technologies in terms of their performance can also inform application-specific choices, such as OLED for a foldable mobile device where flexibility and contrast are more important or LED for outdoor signage where maximum brightness is important. The analysis is limited by the reliance on secondary literature more than on actual experimental data; that is, some of the cited performance results may already be outdated due to the rapid development in this field. Moreover, the analysis does not take into account the regional supply chain differences or recent geopolitical factors with respect to display material availability which could also affect the cost and manufacturing information in the study. Moreover, coverage of EL-QLED technologies is limited, and most performance data available in the literature come from lab-based demonstrations rather than commercial products. Future research would be useful to do direct experimental comparisons of OLED and EL-QLED devices in the testing laboratory under standardized conditions, especially the blue emission efficiency and T95 lifetime. To further enhance the life cycle analysis with the latest

manufacturing energy data, cadmium-free InP quantum dot technology should be evaluated to determine whether it can close the current performance gap with CdSe-based quantum dot materials. The study in general has deepened the understanding of the multi-dimensional trade-offs in LED, OLED, and QLED and the application context for display technology. This study examines the physical basis and practical limitations of each technology and thus sets the stage for more nuanced and relevant comparisons to more academic and industrial applications in future research and work.

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