Progress and Remaining Challenges for MicroLED Volume Manufacturing

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ABSTRACT

Various companies are investing massively to set up the manufacturing infrastructures and foster full ecosystems and supply chains to prepare volume production of MicroLED displays for consumer applications. However, problems remain that could further delay the long-expected transition of microLED from the lab to the fab.

1 Introduction

Micro-light emitting diode (µLED) is an emissive display technology in which each individual red, green, and blue sub-pixel is an independently controllable light source: a tiny LED chip, less than 100 µm in size, ideally less than 50 µm for consumer applications. Just like Organic Light Emitting Diodes (OLED), they offer high-contrast, high-speed, and wide viewing angles. In addition, they could also deliver a wider color gamut, much higher brightness, significantly reduced power consumption, improved lifetime, ruggedness, and environmental stability. Finally, µLEDs could allow the integration of sensors and circuits, enabling thin displays with embedded sensing capabilities, such as fingerprint, in-display camera, touch function, gesture control and more.

Spearheaded by efforts from Apple and others, µLED has generated a lot of excitement over the past decade. All leading display makers now have sizable µLED development efforts. The supply chain is shaping up, with alliances and takeovers amongst large LED and display makers. As some leading players are starting to establish volume manufacturing capacities, the industry is entering a “make or break” era. The success (or failure) of those first large-scale manufacturing efforts will decide on the fate of the technology.

2 MicroLED vs. OLED: a moving target.

MicroLEDs promised better performance than OLED on all key metrics, however, they are facing ongoing delays due to manufacturing challenges and costs. Meanwhile, OLED is now a ~$40B/year industry with more than $100b cumulated investment in OLED fabs. There are technology roadmaps and massive investments plans pushed by strong players in Korea and China to keep improving OLED cost, performance and power consumption. With the availability of blue phosphorescent materials [1], the efficiency of RGB OLED displays used in mobile devices will increase 20-25% from 2025. For White OLED (OLED) and blue OLED + Quantum Dot architectures (AKA “QD-OLED”), improved blue efficiency will allow to decrease the number of emitting layers, enabling significant cost reductions.

Figure 1 shows that many other upcoming OLED improvements will contribute to additional performance gains (efficiency, brightness, lifetime etc.) and cost reductions. Those include micro-lens for light extraction, tandem structures for increased brightness and reduced burn-in, oxide backplanes and new, generation 8.7 fabs for larger mobile devices (tablet, laptops) as well as lithographic patterning, which could boost lifetime 3-6x and brightness by up to 2-4x. In the longer term, plasmonic OLED architectures could further improve lifetime and bring the External Quantum Efficiency above 40%, significantly higher than any microLED [2].

Fig. 1 OLED technology and manufacturing roadmap with TRL (Technology Readiness Level)

As OLED keeps improving the value proposition of µLED is becoming less obvious. In other words, the opportunity of differentiation is shrinking. There is therefore a sense of urgency for µLED to succeed before OLED becomes too entrenched in most applications.

3 MicroLED display costs.

3.1 Major cost drivers

Cost remains a major issue for µLED and has been discussed at length [3], [4]. Up to 20x cost reduction is required for some applications (TV) to compete with

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OLED. The industry has clear and credible, yet aggressive and challenging roadmaps to bring costs down to a level that could enable high-volume consumer applications such as TVs, wearables, automotive, laptops or even smartphones. Success will depend on the ability of the industry to follow this aggressive, technology-driven cost-reduction roadmap and the will to invest in building the supply chain. For the latter, am-Osram’s decision to build a $880 million, 200 mm dedicated microLED fab is an encouraging step. Other efforts by Epistar, HC Semitek or Sanan could bring healthy competition and multiple sources of high-performance, cost-effective µLED die. Key opportunities for cost reduction indeed include smaller die size, improved mass transfer throughput, yield management strategies and repair processes.

<table>
<thead>
<tr>
<th>Cost reduction opportunity</th>
<th>4x to 40x</th>
<th>8x to 70x</th>
<th>1x to 50x</th>
<th>15x to 2x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single largest cost contributor to kill of materials</td>
<td>$250</td>
<td>$500</td>
<td>$1000</td>
<td>$2000</td>
</tr>
<tr>
<td>2nd or 3rd largest cost contributor</td>
<td>$100</td>
<td>$200</td>
<td>$500</td>
<td>$1000</td>
</tr>
</tbody>
</table>

Import on Total Cost: Single largest cost contributor to kill of materials

Die size is not improved, they won’t be able to deliver harder with low pixel density. Other players might go down this die size reduction path faster: most demos from AUO, PlayNitride, Tianma or X-Display in 2023 already use similar or slightly larger die: 20x40 µm, 13x20 µm, 15x30 µm, 8x15 µm etc.

Additional cost reductions could be enabled by the adoption of even smaller die. This, however, would require using vertical LED structures. Those are more challenging in term of both LED manufacturing and display integration (figure 4). For example, because vertical dies require the deposition of a top electrode to test the pixel, repair, i.e., removing a bad die and replacing it with a good one, becomes challenging. For those reasons, most of the industry has so far focused development on easier, horizontal flip chip structures.

Efforts to develop and integrate vertical die however are accelerating. Apple, which has focused exclusively on vertical structures, will use 6 to 9 µm vertical die in its smartwatch expected to be released in 2026.

Smaller dies pose an additional challenge for TVs: with low pixel density displays, each die must work harder to deliver a given brightness. If the EQE of small die is not improved, they won’t be able to deliver the high brightness consumers expect from a µLED TV.

3.2 Die cost

Samsung’s commercial 89” µLED TV was finally introduced in 2023 in selected markets for around US$105,000, the µLED die are the single largest contributors. The TV uses 34x58 µm die for which we estimated the total cost at more than $17,000 in 2022. However, we believe that under a combination of µLED Chip-on-Wafer (often referred to as “CoW”) cost, and die size reduction to 8x15 µm, this could decrease to less than $250 within the next 5 years (Figure 3).

3.3 Backplane cost

With a clear, although aggressive roadmap to bring microLED die cost within an acceptable range for high-end TVs, the major roadblock might become the backplane. MicroLED driving is more complex than OLED due to the significant wavelength shift with current and temperature, as well as the nonlinear efficiency curves of LEDs. A combination of Pulse Amplitude and Pulse Width Modulation (PAM+PWM), AKA analog/digital hybrid driving, delivers the best results, but requires complex circuits. Samsung’s µLED TV requires 19 transistors per subpixel. Only LTPS backplane technology can deliver sufficient performance and compacity with µLED. Even though, because they can’t output enough current, TFTs can be a limiting factor for
brightness in large displays, including TVs.

The cost of LTPS, while acceptable for small displays such as smartwatches, phones, tablets, laptops, or automotive panels, becomes prohibitive for large areas. In addition, LTPS TFT is manufactured on smaller glass generations, typically Gen. 6 (1500 x 1850 mm²), from which it is not possible to economically extract large, TV-sized panels. As a result, µLED TVs (and other larger displays) are produced by assembling (“tiling”) together, smaller modules. For example, Samsung’s 89” TV is based on an array of 7x7 = 49 LTPS modules, each 12.7” in diagonal. This modular assembly also requires complex interconnects to carry electrical signals from driver ICs situated at the back of the module to the TFT circuits and the LEDs on the front. This is achieved with edge electrodes which are complex and expensive to realize.

Process integration is challenging as well: each module requires complex front plane processing for the TFT circuits (up to 20 lithography steps), backplane processing and edge processing from signal routing to and from the TFT and backside driver ICs. Each of those steps adds to cost and yield losses: processing the backside without damaging the TFT on the front and adding the edge electrode without damaging the front or back of the module is difficult. As a result, yield losses can be steep and affect modules to which a lot of value has already been added. Reports of yields as low as 5% initially for LTPS module manufacturing give an idea of the challenge.

The cost of LTPS might remain prohibitive and prevents from achieving an acceptable high-end TV price below $5000. High-mobility oxide materials could be the solution. Multiple display makers and research organizations are working on developing oxide TFT materials with mobilities that would rival that of LTPS. Samsung, Sharp, Japan Display, TCL-CSOT, BOE are all targeting oxide carrier mobilities in the range of 50 to 100 cm²/V.s. If such results can be economically transferred into high-volume production, the simpler, more economical oxide TFT manufacturing process could then enable more acceptable backplane cost, similar to that of existing OLED TVs.

4 Microdriver ICs.

Another compelling and disruptive alternative however would be the use of microdriver ICs. Microdrivers are small, un-packaged, Si-CMOS integrated circuits positioned on the front plane and assembled by the same mass transfer techniques used to assemble the µLED die (Figure 6).

Hybrid, Active/Passive matrix architectures, can significantly reduce the number, size and cost of microdriver ICs. Here, the display has a global active-matrix architecture comprised of smaller passive-matrix-driven pixel clusters, organized around a single driver IC, each using Time Division Multiplexing to drive multiple rows of pixels.

Increasing module size and reducing I/O complexity is therefore a major thrust area. Ideally, a “N x 2” architectures would ensure that each module is connected via an open edge (Figure 5). This however requires larger tiles which, in turns, could impacts TFT yields. However, even with significant cost reduction and yield improvement, the potential benefits of microdrivers are compelling: they could deliver superior performance enabled by Si-CMOS circuits at a cost lower than that of LTPS. Performance benefits include: higher brightness, improved stability, higher grey scale resolution (color depth and contrast) and complex functionalities such as Memory in Pixel or driving in-plane sensors [5]. Last but not least, they would deliver significant reduction in power consumption by reducing the voltage gap between the transistors and the µLED, and enabling the driving of LED
at peak efficiency [6], [7]. Sony’s Cledis, the first commercial µLED display introduced in 2017 used an architecture with one microdriver per pixel. X-Display demonstrated displays using AM/PM hybrid architectures. Similar concepts have been discussed by other companies such as Vuereal, PlayNitride, V-Technology, Sapien etc. Our cost modeling shows that microdriver architectures could deliver lower cost than LTPS.

For TV, the backplane cost could be the showstopper. To reach the $5000 mark and open the door to a small yet profitable size of the high-end TV market, the industry needs to find alternatives to LTPS. Next generation oxide materials could be the solution, enabling, single monolithic (single panel) and lower cost TFT backplanes. The single panel solution also eliminates costs associated with backside and edge module processing. However, it also eliminates a very desirable features of µLED which is the ability to build displays of any size by assembling individual modules. Silicon CMOS microdriver ICs would be a very disruptive alternative in term of both architecture and supply chain. Rather than necessitating billion dollars TFT fabs, microdrivers can be sourced from multiple, existing CMOS foundries. They would enable dramatically enhanced performance and reduced power consumption.

**REFERENCES**

[1] G. Dickson “UDC’s Phosphorescent Blue on Track for 2024 Launch”, [https://doi.org/10.1002/msid.0050033](https://doi.org/10.1002/msid.0050033)


