

# Status of the MicroLED Industry: Technology and Equipment Thrust Areas for Success

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## Abstract

MicroLED is a promising display technology but to succeed, it must deliver differentiating performance, at a cost similar to that of OLED. Significant progresses have been achieved. However, a new impulse is needed in terms of technology, equipment and manufacturing infrastructure to deliver consumer-grade quality display.

## Author Keywords

MicroLED, emissive displays, manufacturing, equipment, driving, tiling, efficiency, metrology, inspection, mass transfer.

## 1. Introduction

More than two hundreds microLED displays demos have been presented over the last 8 years by close to 50 companies [1]. They encompass all sizes, pixel density and form factors, as well as flexible, transparent and stretchable displays. With the likely exception of smartphones, virtually any display applications could be addressed by microLEDs. However, after remarkable improvements through 2020-2023, the quality of the prototypes seems to be plateauing. Breakthroughs in terms of cost and quality have yet to materialize. Apple’s cancellation of its ten year, \$3B microLED smartwatch project also raised concerns about the prospects for the technology [2].

While this plateau is not an absolute performance ceiling, a new impulse is needed to eliminate defective pixels, haze, screen door effect etc. More than anything, cost remains too high, by a 3-4x factor (smartwatches) all the way to more than 10x (television).

We consider 4 major technologies, and 4 categories of equipment and manufacturing infrastructure thrust areas to enable microLED high volume commercialization.

## 2. Technology Thrust Areas.

MicroLED is still a relatively young display technology. It combines technology and manufacturing know-how from various industries: LED, displays, semiconductors.

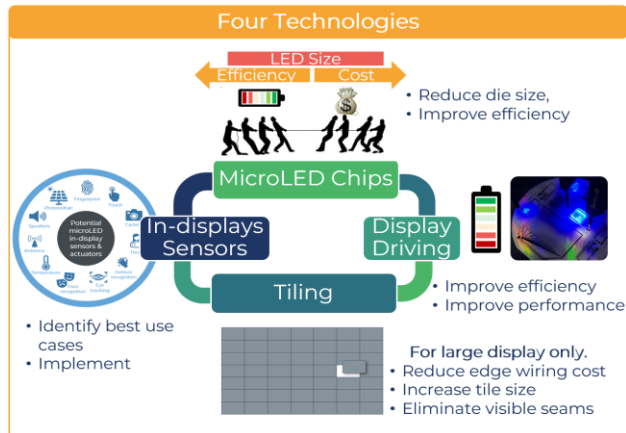


Figure 1. Major microLED technology thrust areas

A major culprit is microLED die, the single largest contributor to the Bill of Material (BOM) of microLED displays. With cost loosely proportional to chip area, the large die size, typically 450 to 2000  $\mu\text{m}^2$ , used in most prototypes are a cost dead end. It is widely agreed that die sizes closer to or below 100  $\mu\text{m}^2$  are required for most consumer applications [3]. Small die, on the other hand, are currently in a technology dead end: their lower efficiency leads to high power consumption compared to OLED.

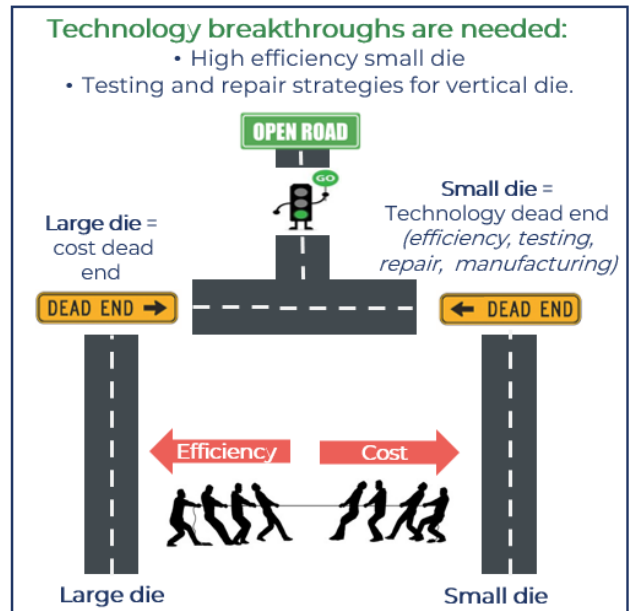


Figure 2. are microLED chips in a technology dead end?

A breakthrough is therefore needed to improve the efficiency of very small die. Small sizes also imply a vertical die architecture which requires the development of suitable testing and repair processes as well as specific equipment and display architectures.

There is still headroom for higher efficiency. New EQE (External Quantum Efficiency) records for very small die are announced on a regular basis. Thrust areas include improved die edge passivation, current confinement structures and bottom-up growth processes that eliminate mesa etching [4], [5], [6], [7].

Translating those results into volume production however will require microLED dedicated fabs with a semiconductor-like infrastructure and operating mindset.

For display driving, microLED requires more complex circuitry than OLED. Thin film transistors (TFT) are very large. As the pixel density increases, the space available to fit those transistors shrinks. For high pixel density such as in smartwatches or smartphones, fitting more than 5-7 transistors within each sub-pixel is challenging. This limits the complexity and functionalities that TFT could deliver. In addition, due to the large

voltage mismatch between TFT and the LEDs, 30 to 50% of the power is wasted in the TFT.

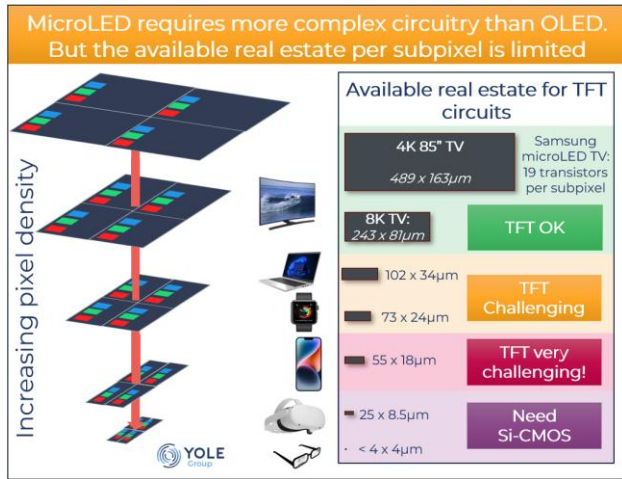


Figure 3. Impact of pixel density on available subpixel real estate from TFT circuitry.

Silicon CMOS transistors on the other hand could push much higher currents at higher efficiency and integration density. This can be achieved with the use of Si-CMOS microdriver ICs assembled with the same mass transfer techniques used for the microLED chips.

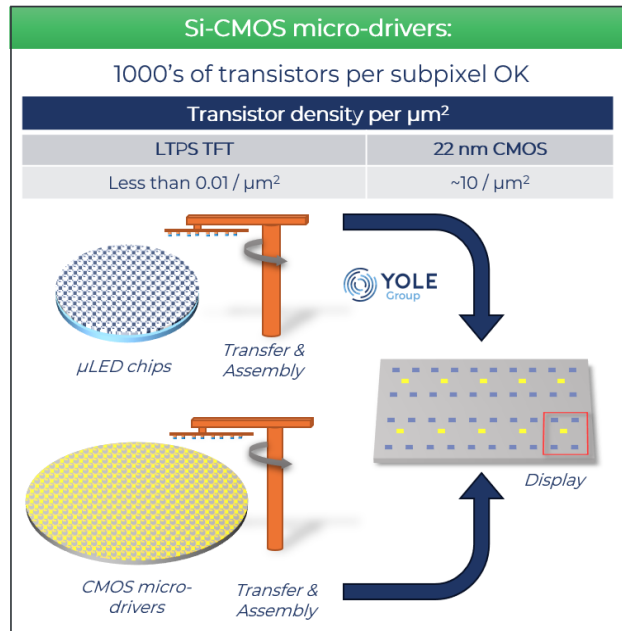


Figure 4. microdriver-based microLED displays

Thousands of transistors per subpixel could enable advanced functionalities and further reduce power consumption by driving each LED at peak efficiency or refresh only the pixels that need to, rather than doing a full raster scan. Microdrivers however pose their own set of challenges including cost and integration. Hybrid, multiplexed architectures driving passive matrix clusters of 8 to 64 pixels reduces the required CMOS area [9].

Microdrivers could also enable the integration of in-display sensors and carry displays into a new era, bringing together top performance, multi-sensing capabilities and AI to deliver the ultimate “Smart Display” [8], [9], [10], [11], [12].

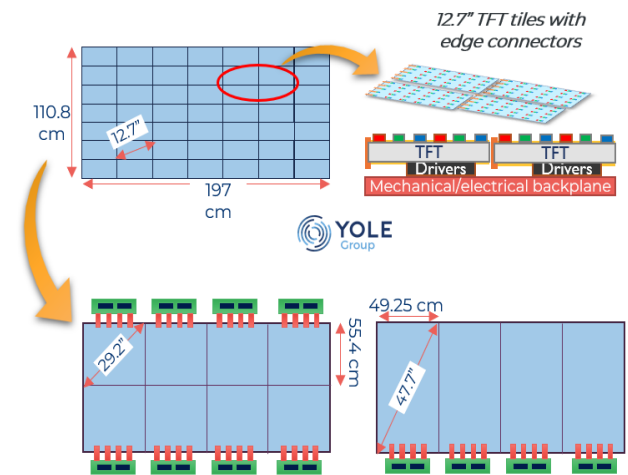
The industry however is not clear yet about which sensors and functionalities to focus on. Sensors add complexity while microLED makers are already struggling to bring simpler displays to market. For most, the priority is to bring a first generation of TFT-based displays to market in order to incubate future generations, before considering adding more complexity and cost. Others however, see those advanced functionalities as the way to differentiate from OLEDs.

Finally, tiling, the ability to create displays of virtually any sizes and shapes by seamlessly assembling smaller modules is a necessary condition to produce large displays such as TVs. This could be a strong element of differentiation versus OLED and LCD, enabling the production of displays of sizes not achievable with monolithic TFT, and doing so with small modules produced efficiently produced on Gen. 6 or below fabs.

Tiling however poses some challenges. Carrying electrical signals between the front (LEDs) and back (Drivers) sides of the module requires double side processing and edge connections. Eliminating visible seams and discontinuities from module to module is critical. Those can originate from physical and mechanical issue such as gaps between modules, light leakage at the edges or variation in reflectivity, as well as from “electronic” module-to-module variability in terms of brightness, color etc.

Ensuring that the seams between modules are invisible out of the box and over the lifetime of the displays is challenging. Mechanical shocks, thermal cycling and natural aging could alter the initial perfect alignment and module-to-module calibration.

More effort toward increasing module size to reduce the number of edge connections and eliminating physical seams through module edge engineering, diffusers and coating is also required.

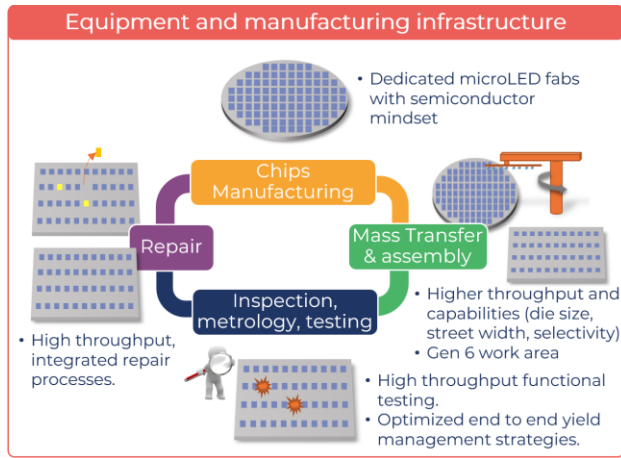


Construction of an 89" display; larger modules enable architectures where each module has access to an open edge of the display. This reduces the number of edge connectors and simplifies manufacturing, even allowing the use of Chip on Film connections

Figure 5. Structure of Samsung's 89" microLED TV (top) and effort toward larger modules to simplify interconnects (bottom)

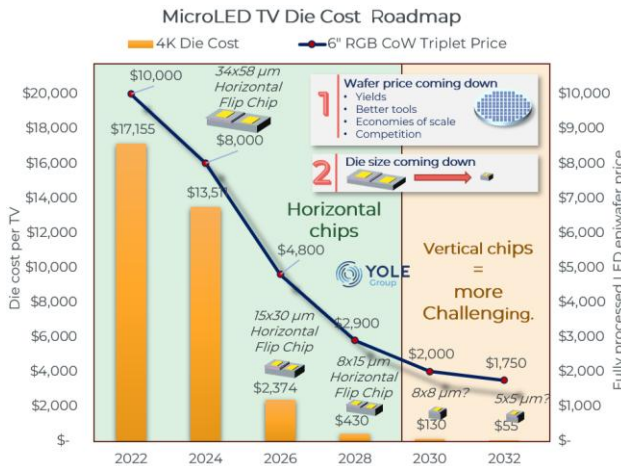
### 3. MicroLED Manufacturing Equipment and Infrastructure

Equipment and manufacturing infrastructure must also mature to enable cost-effective and high-volume production of consumer displays.



**Figure 6.** microLED equipment and manufacturing infrastructure thrust areas.

MicroLED die cost reduction will come from a combination of die size reduction as well as improvement in the manufacturing infrastructure and economies of scale. The latter could lead to a roughly 5x reduction while size could decrease more than 30x.



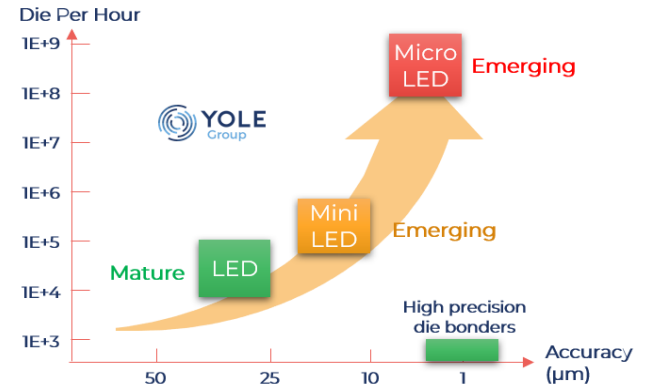
**Figure 7.** MicroLED TV die cost reduction roadmap

The supply chain however must come into place to enable cost-efficient production of very small die. With the demise of Osram’s 8” microLED fab, there are currently no high-volume suppliers of high-performance, sub 100 μm<sup>2</sup> die. With the loss of Apple as a champion, the industry is back to its initial conundrum: large investment and mass production would be required to enable a price where mass production makes sense.

MicroLED chip makers are considering various approaches. Some are attempting to upgrade existing LED production lines to produce microLED. We believe that this strategy will quickly find its limit: with insufficient clean-room levels, older, low performance equipment, reduced automation, etc., yields will hit

a wall as die size decreases. MicroLED die production should ideally be done in greenfield, dedicated microLED fabs, built with a semiconductor-like infrastructure and operating mindset, that is, high level of automation and end-to-end yield management. Additionally, an 8-inch substrate platform could leverage legacy CMOS equipment and process toolbox with the ability to deliver high yields, process capabilities and performance at the lowest cash cost. This approach however implies large investments and initially high depreciations costs. Various players are adopting a middle of the road approach, building greenfield, 6” lines with incremental improvement over traditional LED fabs: better clean rooms, i-line steppers, improved automation etc.

Mass transfer has long been seen as the primary roadblock for microLED displays: success in high-volume consumer applications can’t happen unless robust, high-throughput, high-yield, low-cost-of-ownership mass-transfer equipment is available. Assembling an 8K resolution (7680x4320 pixels) microLED display implies transferring and assembling ~100 million chips the size of bacteria, with a placement accuracy of ± 1μm, and doing so in less than 10-20 minutes to be economically viable. With a best-in-class semiconductor high-accuracy chip bonder, it would take 11 years to assemble a single 8K TV. No standard LED or semiconductor equipment today can manipulate the very small microLED die required for smartphone or TV applications anyways. There is a need for more than five orders of magnitude improvement in throughput compared to established, pick-and-place chip transfer processes and tools.



**Figure 8.** required microLED assembly equipment capabilities compared to existing LED and semiconductor tools.

Progresses on that front have been quite impressive, only 5 years ago, a company willing to produce a microLED display had to invent its own mass transfer technology and build the equipment. As of early 2025, more than 20 mass transfer tools are commercially available from more than 15 reputable equipment makers. They fall into two categories: stamp-based transfer (PDMS stamps) and laser transfer. Although no commercial tools are available to date, fluidic self-assembly remains an active area of research. It could become a disruptive solution, or at least, a welcome addition to the existing toolbox.

The performance and total cost of ownership of existing commercial mass transfer tools is sufficient for pilot lines and first products, but not to enable massive adoption in consumer products.

We believe that mass transfer throughput could increase by a factor of 4x to 6x. Multi-head tools can enable further improvement. Increasing the tools' work area also improves productivity, allowing panel makers to handle larger substrates with multiple displays and enabling larger modules for tiled displays. The typical work areas on the first generation of tools were 370x470mm<sup>2</sup>, corresponding to a G2 glass panel. AUO and its equipment partners are setting up a G4.5 (1660x934 mm<sup>2</sup>) production line in 2025. We believe that Kulicke & Soffa's custom tool developed for Apple was a full G6 with 4 transfer heads. Ultimately, most panel makers are targeting G6 (1500x1850 mm<sup>2</sup>) work areas. There are no fundamental technology roadblocks, but such tools are complex and expensive to develop. Only companies that have strong commitment from large display makers will be willing to invest in such an effort.

	2024 Typical	2024 Champions <sup>III</sup>	Long Term Goals	Max gain
Stamp size	40 x 40 mm <i>(in-situ bonding)</i>	100 x 100 mm <i>(ex-situ)</i>	60 x 60 mm <i>(in-situ)</i>	2.25x
# of Heads	1	2	4 <sup>[1]</sup>	4 x
Cycle Time	15 s	10 s	8 s	1.9 x
Throughput	0.4 m <sup>2</sup> / Hr.	2.6 m <sup>2</sup> / Hr.	6.5 m <sup>2</sup> / Hr.	17 x
Work Area	G2	G4.5	G6	16 x

[1] champion values for each categories separately. No players has yet combined all three champion values and achieved 2.6 m<sup>2</sup> / Hr.

**Figure 9.** potential productivity gains for microLED mass transfer equipment.

Yields is the single largest manufacturing cost: high cost of repairing defective pixels plus cost of discarded products at each level of the manufacturing process. The major culprit is the high defectivity on microLED wafers (typically > 0.5%). This ties back to the lack of dedicated microLED fabs. But even once in place, a few 1/10th of percent defects would still lead to thousands of randomly distributed defective pixels. The industry therefore needs cost-effective functional testing solutions to eliminate bad die from the workflow before assembly, as well as cost efficient repair tools. Probe-based functional testing tools are now available with throughput in the 6-12M DPH range. While sufficient for small display production (smartwatch), larger displays such as TVs could require up to 10x faster and the ability to handle very small die. Massively parallel, contactless testing could be a solution but lacks maturity. The first commercial is still being evaluated by various manufacturers.

For LED-On-Si microdisplays used in Augmented Reality headsets, improving red emission efficiency and architectures for full, monolithic RGB microdisplays remains challenging. Process integration is also an issue. Many players are striving to develop processes compatible with CMOS fabs<sup>[13]</sup>. Making microLED in an existing CMOS line however would leave many pieces of equipment idled. A dedicated line built for microLED on the other end would be difficult to fill up to capacity. Sharing a line with Power GaN products could help justify such investment.

#### 4. Conclusion

The microLED industry is at a crossroad. As microLED keeps getting delayed and OLED keeps improving in term of both cost and performance, the value proposition of microLED is shrinking, creating a sense of urgency to accelerate commercialization.

Breakthroughs are needed in terms of technology, manufacturing process and equipment. None of the identified roadblocks appear to be fundamental limits. Multiple paths often exist to keep advancing the technology and performance, many players have clear roadmaps to do so. However, execution will require long term commitment and significant investments that many companies are still hesitant to commit to.

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