Will microLED succeed in high volume consumer applications?

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Abstract

Back in 2017, many were confident that microLED commercialization would start by 2020 or 2021, but as volume adoption keeps getting delayed, the sprint has turned into a marathon. Nevertheless, the efforts toward commercialization are accelerating. The supply chain is shaping up, with alliances and takeovers amongst large LED and display makers. Various players are starting to establish volume manufacturing capacities. MicroLED promised better performance than OLED on all key metrics. But as microLEDs keep getting delayed while OLED keeps improving, microLEDs' value proposition in some applications could become less clear.

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.

MICROLED DEVELOPMENT AND MANUFACTURING EFFORT.

We estimated that exiting 2023, the microLED industry had collectively spent $11.8B in developing and preparing microLED for volume manufacturing. This breaks down into $6.7B for R&D (with about 38% of that stemming from Apple alone), $2.2 in startup funding, $691M for pilot lines, and already more than $2.2B in manufacturing infrastructure. The latest is, again dominated by Apple's efforts to set up the supply chain for a microLED smartwatch with, most notably, ams-Osram building a $1B greenfield, 200 mm microLED fab to serve the consumer electronic giant's need for microLED chips. To those numbers, one could also add $2.4B of acquisitions as large companies such as Apple, Meta, or display makers BOE and AUO have acquired stakes in or fully acquired microLED startups and LED makers.

MICROLED CHIP MANUFACTURING WAFER PLATFORMS

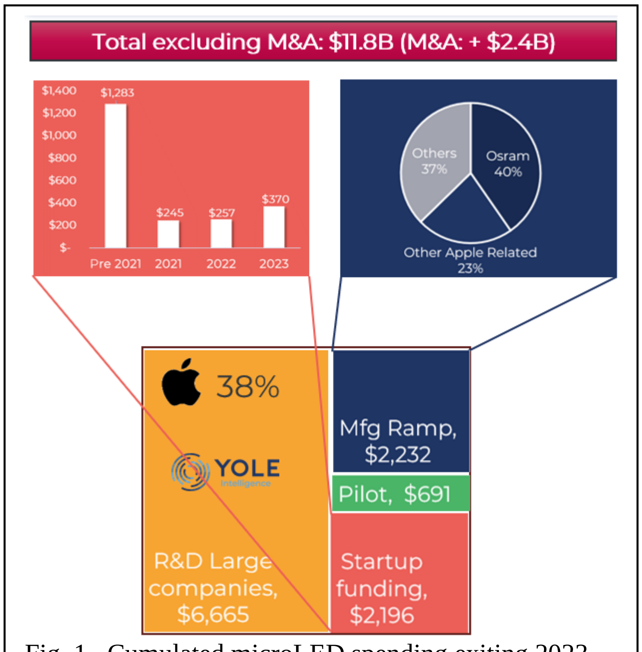

Fig. 1. Cumulated microLED spending exiting 2023 (Yole Group estimates) [1].

Apple's and Osram's decision to go for a 200 mm platform which will produce green and red chips on sapphire substrates and red chips on GaAs is a bold move: the traditional LED industries mostly relies on 4-inch (100 mm) wafers, with some exceptions such as Osram, Lumileds or LG which have pioneered adoption of 150 mm wafers.

Most microLED fab projects from companies such as HC Semitek (recently acquired by display giant BOE), Epistar or San'an are focused on 150 mm, or even 100 mm (Jade Bird Display) wafer platforms. There are some exceptions however, with various companies such as Aledia, Stratacache, Enkris or Porotech making a bet on a different substrate and technology platform: GaN-On-Si.

Many LED makers conducted initial microLED work in existing, often mostly depreciated LED fabs. Those deliver low manufacturing costs, well suited for early stages of development. However, because the microLED chips are the single largest contributor to the bill of materials, there is a strong incentive across most applications to dramatically shrink die size. Certain applications like smartphone will require dies smaller than 5 µm. Traditional LED fabs are ill-fitted for such efforts. As die size decreases and performance requirements increase (efficiency, homogeneity etc.), defectivity will increase, driving yield costs to unsustainable levels, while performances hit a ceiling due to equipment not fit for the task.

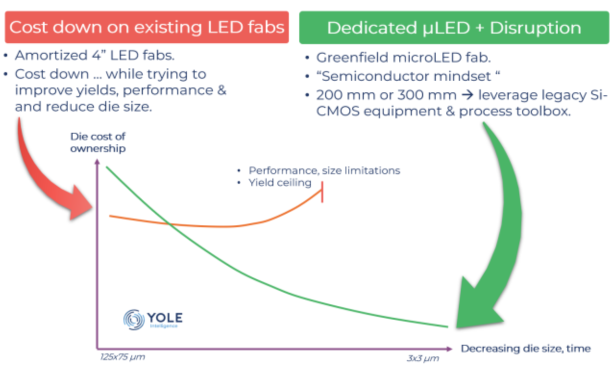

Fig. 2. Comparing approaches for microLED chip manufacturing

MicroLEDs therefore require a paradigm shift toward a semiconductor-like manufacturing mindset. This means not only better equipment and cleaner manufacturing environment, but also high levels of automation, end-to-end defect prevention and yield management strategies etc. Switching to an 8" or even 12" manufacturing platforms opens access to robust, battle-tested, highly automated traditional semiconductor equipment delivering high-yield and a vast process toolbox not available in traditional LED fabs. This greenfield approach initially requires high capex. However, we consider that in the long term, it is the most credible path for the cost effective, high-yield production of the very small, high-performance microLED die that are required to enable the most challenging applications such as consumer TV or smartphones.

Beside improving epi and chip processing efficiency, adopting larger diameters also enables higher wafer utilization for mass transfer by reducing edge losses when transfer stamps pick up chips for the donor wafers for transfer toward the final display or an intermediate carrier.

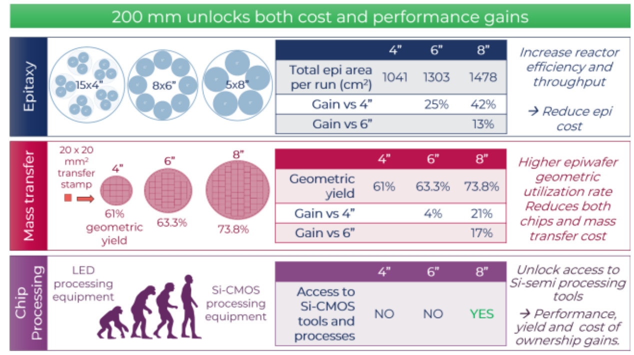

Fig. 3. Benefits of larger wafer platforms for microLED manufacturing

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 $120b 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 [2], the efficiency of RGB OLED displays used in mobile devices could increase 20-25% from 2025 or 2026. 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.

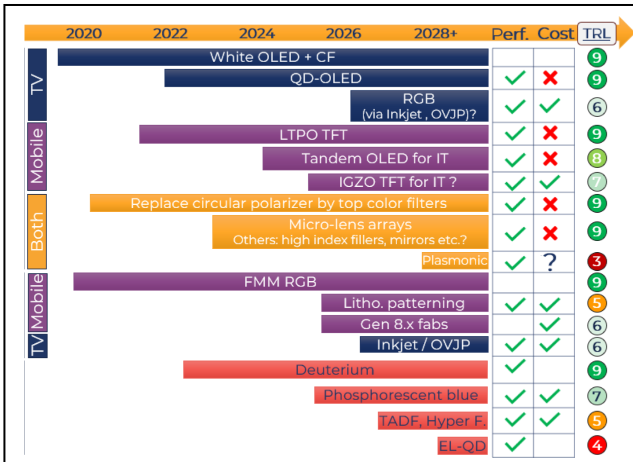

Fig. 4: OLED technology and manufacturing roadmap and Technology Readiness Level (TRL)

Figure 4 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 [3]. As OLED keeps improving the value proposition of microLED 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.

MICROLED DISPLAY COSTS

Cost remains a major issue for µLED and has been discussed at length [1], [4]. Up to 20x cost reduction is required for some applications (TV) to compete with 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. Key opportunities for cost reduction indeed include smaller die size, improved mass transfer throughput, yield management strategies and repair processes.

	Die Size	Transfer & Assembly (Stamp Size, Cycle time, Tool Cost)	Yield & Repair	Manufacturing Efficiency
Cost reduction opportunity	4x to 400x	8x to 120x	1 to 50x	1.5 to 2x
Impact on Total Cost	*Single largest contributor to bill of materials*	*2nd or 3rd largest cost contributor in 2023*	*Single largest manufacturing cost contributor*	*Applies across most steps*
Comment	Cost scales with the chip's total area (die + street width)	Increase transfer area Current tools: 15x15 to up to 50x50 mm² stamp), cycle time: 10-30s	2023 combined yields < 99.5%. Improving to 99.99% could reduce repair cost 50x	Adopt semiconductors manufacturing mindset (large wafers. High automation, yields...)

Fig. 5: major opportunities for microLED cost reductions.

Looking more specifically at 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 cost, and die size reduction to 8x15 µm, this could decrease to less than $250 within the next 5 years. Other players might go down this die size reduction path faster: most demos from AUO, PlayNitride, Tianma or X-Display in 2023 already used similar or slightly larger die: 20x40 µm, 13x20 µm, 15 x 30 µm, 8 x 15 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 (fig. 6). 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 or 2027.

MICROLED DISPLAY PERFORMANCE

It is unlikely that MicroLEDs will be able to compete on costs against OLED. To succeed, the technology must

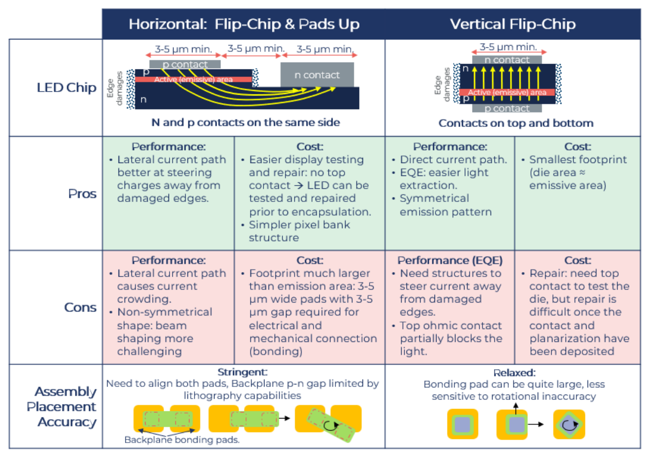

Fig. 6: comparison of horizontal and vertical die structure

therefore offer significant performance differentiation against incumbent display technologies.

The value proposition of microLED differs depending on the application: mobile devices such as smartwatch, laptops, tablets or smartphone value power consumption and battery life. Viewing angle are important in smartwatches but less critical in laptops. Longevity and image sticking (AKA "Burn in" are an issue in notebooks which displays can be on for 8 hours a day or more. Very high brightness (million of nits levels) are required for augmented reality glasses etc.

As a self-emissive technology, microLED will retain all benefits of OLED and could improve on many, but it is critical that microLED leverage on its unique characteristics that no other technologies can offer. One such feature is the ability to build modular display of any desired size by tiling smaller modules. Samsung's 89" microLED TV for example is built from a matrix of 49 (7x7) 12-inch modules. Because LCD require a seal for the liquid crystal and OLED an encapsulation to protect the fragile organic materials from oxygen and moisture, microLED is the only technology enabling seamless, bezel-free tiling. While tiling comes with its own challenges, the use of smaller modules is also beneficial for yield: rejecting a single 12” modules if more cost effective than having to reject a full 89” panel.

MicroLED also excel at transparent displays. Because they can be driven at high currents without risk of damage, microLED can be very bright compared to OLED. The emitting area required for a given display brightness is much smaller. This enables very high aperture ratios (the ratio of the pixel to emitter area). This favors contrast for all displays but is especially beneficial for transparent displays. Transparency is desirable in a variety of applications such as retail, public information displays, and automotive or other modes of transportation.

The combination of the two above-mentioned characteristics, i.e. small emitters and encapsulation-free architecture, enables another unique category: stretchable displays. Stretchability is hard to achieve with displays. One promising avenue is to combine small rigid islands containing the emitter and driving circuit, with stretchable conductors (Fig. 7).

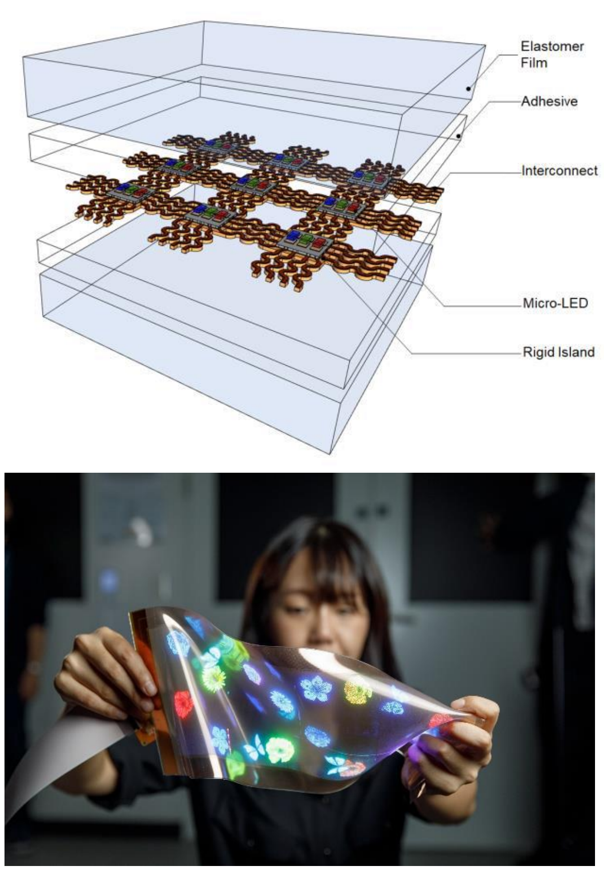

Fig. 7: structure and actual microLED stretchable display [5]

Because the ratio of the rigid to stretchable area dictates how stretchable the whole display is, microLED are at an advantage due to the very small size of the emitters. For OLED, the need for encapsulation is also problematic when building stretchable displays. Today there are no satisfying stretchable encapsulation solutions, so the encapsulation can’t be continuous across the entire display but must be patterned at the pixel level. Stretchable displays could enable freeform displays, flexible along any axis and conformable to any complex surface. Those could be integrated in fabrics. In automotive, they would enable complex shaped design and, combined with actuators, replace physical buttons.

Conclusions

Back in 2017, many were confident that microLED commercialization could start in 3-4 years. But the sprint has shifted to a marathon, with significant adoption still 3-4 years away, and high-volume consumer adoption that could enable microLED to stick for the long term, probably 5 to 10 years away depending on the application. To succeed, microLED will have to deliver differentiating performance compared to incumbent display technologies and do so at a cost comparable to that of OLEDs. This will be enabled by dedicated microLED fabs along with further technological progress in manufacturing, die efficiency and display architectures [6].

References

[1] “Status of the microLED Industry 2023”, Yole Group report.

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

[3] M.S.Weaver, M.A Fusella, R. Saramak, E. Bushati, H. Mundoor, V. Menon, N. Thompson, J. Brown “Plasmonic PHOLEDs: increasing OLED stability”, https://doi.org/10.1039/D1TC05674C

[4] E. Virey and Z. Bouhamri, “Trends Toward Integrated RGB Microsystems for Mini and MicroLEDs: MicroLED in Package and Smart Pixels”, Proceedings of The International Display Workshops, Vol.29, 2022, ISSN-L 1883-2490/29/0878

[5] H. Jung et al. “High-Resolution Active-Matrix Micro-LED Stretchable Displays”, SID International symposium 2023, https://doi.org/10.1002/jsid.1223

[6]: E. Virey et al. “Progress and Remaining Challenges for MicroLED Volume Manufacturing, Proceedings Of The International Display Workshops, Vol.30, 2023

Acronyms

LCD: Liquid Crystal Display
OLED: Organic Light Emitting Diode