MicroLED Display: technology and applications status

Eric Virey, Zine Bouhamri, Claire Troadec

Yole Developpement, Le Quartz, 75 cours Emile Zola, 69100 Lyon Villeurbanne, France

Telephone: +33 472 83 01 80

E-mail: virey@yole.fr

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MicroLEDs promise new generations of displays with improved performance in term of brightness, energy efficiency contrast, color gamut, etc. Many companies have shown prototypes in various sizes and performance, aimed at a wide variety of applications, ranging from augmented reality to automotive, wearables, televisions, public information displays, etc. The first commercial, consumer-oriented microLED displays entered the market in 2021. Yet, despite all its promises adoption of microLEDs remains anecdotal. This paper will discuss the latest developments and remaining bottlenecks for broader microLED adoption.

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.

Many companies have now showed µLED prototypes in various sizes and performance. They are aimed at a wide variety of applications, ranging from augmented reality to automotive, wearables, televisions, public information displays etc. The first commercial, consumer-oriented µLED displays became available in 2021 in augmented reality (AR) headsets as well as in large size, high-end TV sets. However, technology, yield, cost, and supply chain issues still prevent wider adoption.

MASS TRANSFER

The art of making µLED displays consists of processing a bulk LED substrate into an array of µLEDs that are poised for pick up and transfer to a receiving backplane substrate for integration into heterogeneously integrated system incorporating the LEDs, pixel driving transistors, optics, etc. [1], [2]. An 8K display (7680 × 4320) requires close to 100 million individual µLEDs. To ensure proper interconnection and to eliminate certain image artifacts (bright or dim lines due to inconsistent spacing between groups of µLEDs), the required placement accuracy is typically ± 1µm. Today's best die bonders can't manipulate the very small die (3 to 15 µm) required to enable high volume consumer applications. In addition, they typically have throughput in the range of 1000 die per hour. At this pace, it would take more than 11 years to manufacture a single 8K TV. There is therefore a need for a paradigm change: the development of mass transfer technologies that can manipulate and assemble much smaller die than typical pick and place equipment and do so with a throughput at least 5 orders of magnitude faster.

TABLE I
REQUIREMENT FOR µLED CONSUMER DISPLAY ASSEMBLY

	Standard die Bonder *(LED, others)*	MicroLED Display Mass Transfer Requirements
Die size	> 70 µm	3 to 15 µm
Placement accuracy	± 1 µm	± 1 µm
Throughput	< 1000 die / hour	> 300 m die /hour

A continuous monitoring of intellectual property activity indicates that mass transfer has long been and remains a leading thrust area for µLED technology development.

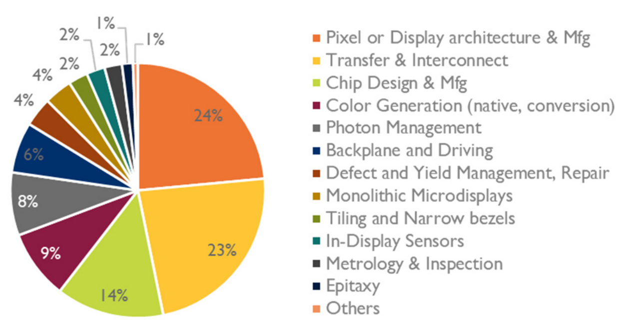

Fig. 1. Breakdown of microLED Display patents by technology nodes [2]

Developing mass transfer processes with sufficient yield and throughput has long been seen as the major challenge for µLED displays. Dozens of processes have been proposed. They can be classified as illustrated in Fig. 2.

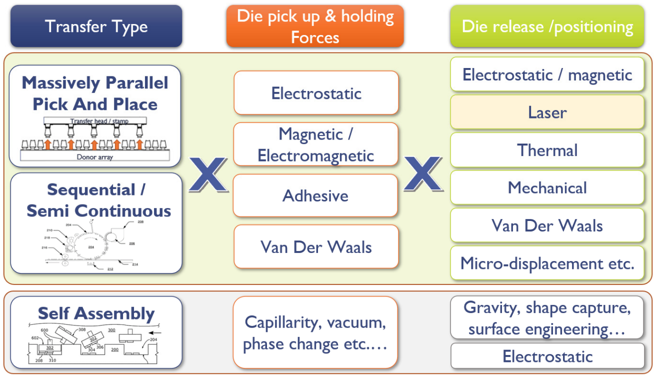

Fig. 2. Classification of mass transfer processes

The most popular transfer methods involve the use of polymer "stamps" (adhesive-coated or not) able to exert a pickup force on a large array of LEDs (tens of thousands or more). Various die-release mechanisms are used, including lasers which has been gaining a lot of traction due to its ability to enable fully addressable processes where only good die identified by upstream metrology and testing are transferred and defective ones eliminated from the workflow. Other methods involved different type of MEMS or self-assembly in a fluid of gas medium.

Progress in mass transfer over the last 5 years has been spectacular, to the point that, as of early 2022, many industry players no longer see it as a fundamental roadblock. There is off course still a long road to get to mature, cost effective, and robust processes ready for high volume manufacturing of consumer µLED displays, but there is now a clear runway ahead. As a result, an increasing number of established semiconductor and equipment makers are now offering commercial µLED mass transfer, repair and testing tools and solutions.

Chip and System Efficiency

Another major thrust area is µLED chip structures and fabrication. Efforts revolve around improving efficiency, devising structures suitable for mass transfer, or creating RGB monolithic chips which could simplify display assembly.

At very small dimensions, µLED operation is impacted by nefarious sidewall effects related to surface and subsurface defects such as open bonds, contaminations, or structural damages in which non-radiative carrier recombination dominate. Sidewall effects result from the harsh manufacturing conditions (plasma etching) and can spread over distances similar to the carrier diffusion length, typically 1-10 µm: not a big deal in LEDs that are 100's of microns large but a killer for µLEDs where they could affect the entire volume of the chip. As a result, the External Quantum Efficiency (EQE) of µLEDs tend to be significantly smaller than traditional LED with sizes above 100 µm.

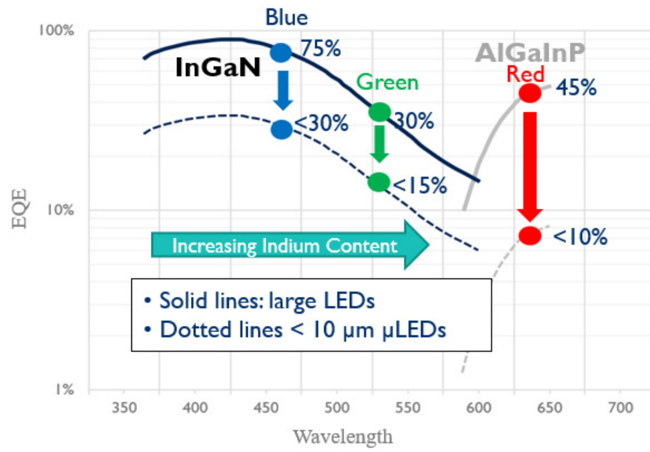

Fig. 3. µLED EQE drop at different wavelength.

The drop in LED efficiency at small sizes is now well documented and its causes are better understood [3],[4]. Researchers have devised various ways to alleviate those effects and improve efficiency, as illustrated in Table II:

TABLE II
STRATEGIES FOR IMPROVING MICROLED CHIP EFFICIENCY

Selected Area Growth & 3D LEDs	Chip Design	Chip Manufacturing
Grow the LED on patterned seeds or through a mask to produce the 3D chip structure without etching → no sidewall damages.	• Tunnel junctions (improved injection) • Current confinement structures • Improved doping profiles • Angled MQW (away from sidewalls), etc.	• Improved etching • Sidewall passivation • Sidewall "repair" (ALD, MOCVD regrowth, etching, annealing…)

While microLED efficiency still falls short of standard-sized LEDs, progress has been significant over the last few years, especially for red emitters that had initially been lagging significantly [5]. Researchers have improved performance with both AlGaInP and InGaN-based systems. The industry now seems confident that µLED will deliver on their initial promise of delivering lower power consumption than OLED displays.

Chip efficiency, however, is just one contributor to power consumption. Display driving is also critical. In an LCD display, the Thin Film Transistor (TFT) is only used as a switch. In self-emitting displays (OLED, µLED), the emitters are current-driven, and performance depends a lot on the capabilities and stability of the driving transistors which inject the current into the LED. Due to their low mobility and poor characteristics (compared to monocrystalline silicon), TFTs are not very efficient current sources. For OLED, 30-40% of the power is dissipated by the TFT. The situation is even worse with µLED due to their lower driving voltage.

Pixel structures and beam shaping are also important to bring the optical energy where it is needed: the eyes of the users. Requirements vary from one application to another. The more stringent requirements are for micro-displays used with Augmented Reality (AR) applications. In AR devices, the image is delivered to the eye via complex optics so that the display doesn't obstruct the users' field of view and the image is superimposed to the real-world view. The acceptance angle of such optics is usually narrow, typically ± 20º. Light emitted outside of this narrow cone is lost. Worse, it can cause optical cross talk, reducing the sharpness and contrast of the image. Once coupled into a waveguide optics, more losses are encountered. Ultimately, the overall wall-plug-efficiency of AR display and optics systems is less than 1%, hence the requirement for very bright displays, ideally exceeding a million Nits per color.

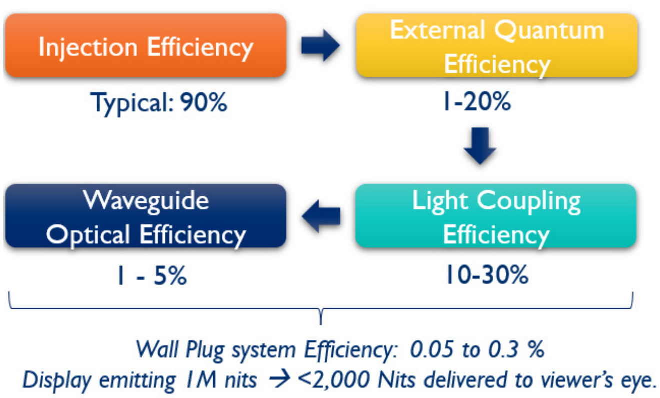

Fig.4. Augmented Reality display and optics system efficiency

Yield Management and Repair

A major challenge for µLED display manufacturer is defect management. In modern displays, dead or defective pixels are no longer acceptable. No matter how good one is at improving epitaxy, chip manufacturing and assembly yields, defective pixels will always occur. Manufacturers must therefore develop effective defect management strategies combining pixel redundancies and/or individual pixel repair, along with chip and pixel testing and binning.

Contribution to defects is spread across the process. A chain is only as strong as its weakest link, and as of early 2022, this remains the LED chip. Defects can occur at the epitaxy level, with particles originating from the environment, the substrate, or the reactor. Most of the defects however stem from subsequent lithography, etching and coating steps that lead to a fully formed µLED chip.

The transfer and electrical interconnects steps add additional defects. Ultimately, even a combined yield of 99.485% (figure 5.) means that, in an 8K resolution TV, more than half a million pixels will be defective.

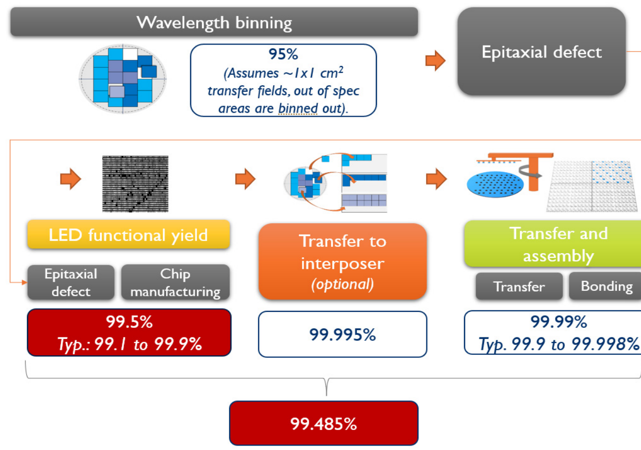

Fig. 5. MicroLED Process Flow and major yield contributors

The industry is striving to reduce this number and deploying various yield management strategies such as die redundancy or upstream testing and selective removal of Known Bad Die (KBD) before they are transferred and connected to the display backplane. Nevertheless, some level of pixel repair will remain unavoidable.

MicroLED Display Cost

Depending on the application, µLED display cost is still 20x to 50x too high to address real consumer products. The challenge appears daunting.

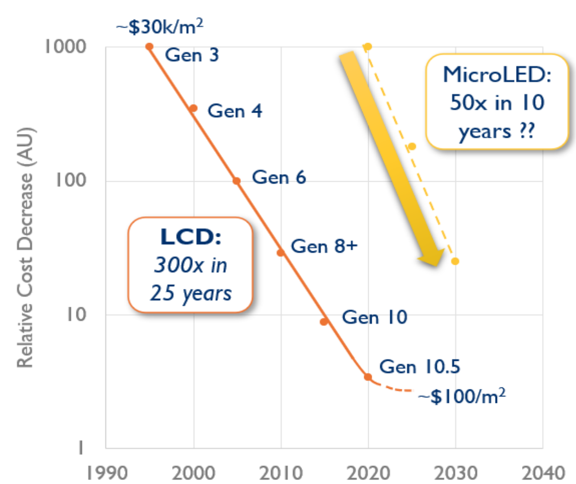

Fig. 6. LCD vs. microLED cost reduction trends

LCD cost decreased 300x, from $30k/m^2$ to $100/m^2$ in 25 years. The situations are different though: LCD started from a blank canvas and cost reduction opportunities lay across the board: materials, equipment, processes, etc. The bulk of it was achieved by generation scaling (substrate sizes). MicroLED, on the other hand, exists at the intersection of the mature Semiconductor, LED and Flat Panel Display industries. There are fewer cost contributors that present 300x reduction opportunities, but in many cases, µLED hasn't yet leveraged on many existing technology bricks and wafer processing equipment that could help deliver a 20-50x reduction at a faster pace than it took LCD.

MicroLED display cost is mostly driven by: 1) µLED die prices, the single largest BOM contributor, and 2) yield management and repair, the single largest manufacturing cost contributor.

Reducing die size is therefore the single largest opportunity to reduce µLED cost. Smaller sizes however reduce LED EQE and increase manufacturing challenges.

Beside size, there are different approaches for LED manufacturing cost reductions: 1) Aggressive cost-reduction on existing 4" LED fabs by pushing capabilities of existing equipment and avoiding investing in new ones. This approach could work for the 1st products (TV, watch, auto) or small displays but delivering very small die sizes will be challenging. 2) Production on 200 mm or even 300 mm wafer in µLED-dedicated fabs. The technology gap and investment are larger with this strategy but, by opening the door to a vast array of battle-tested semiconductor processing tools with high consistency, capabilities, productivity and yields, it could provide companies choosing the option of a large diameter wafer platform a unique cost/performance improvement opportunity in the back end.

Application Trends

For most applications, we struggle to deliver a cost model scenario where µLED is significantly cheaper than OLED, let alone LCD. Strong differentiation is therefore needed. This is easier in segments with no good incumbent technology.

Despite early success in the enterprise market such as warehouse workers, maintenance, medical procedures etc., AR is still in search of a strong use-case for high-volume consumer adoption. It also faces many technological challenges beside displays, including power consumption, form-factor, processing bandwidth, eye tracking, etc. However, when all pieces of the puzzle are in place, µLED is likely to become the only display technology capable of providing the right combination of cost, brightness efficiency and size. But until full color µLED microdisplays are available, LCOS is set to dominate the field.

High price elasticity and strong opportunities for differentiation, such as power consumption, image quality and the ability to integrate sensors and new functions into the frontplane, make smartwatch a compelling case for µLED. Apple is leading the charge on this application with smartphone as the endgame. We expect applications to materialize within the next 2-3 years but see the phone as the most challenging application. This is because OLED displays are already doing a great job in term of both price and performance. To get within the cost envelop for this application, µLED will need to shrink below 5 µm. This compounds all the challenges of low EQE, manufacturability and transfer yields.

Samsung introduced the first µLED TV in 2021, a 110" version, for about $150,000. The company will introduce its second generation in 2022 in 89", 101" and 114". The cheapest model, an 89" 4K is anticipated to retail for around $80,000. This is still about 14x times more expensive than an OLED TV in term of $\$/m^2$. However, compared to the 2021 110" µLED TV model, this represents a more than 45% price decrease in term of $/pixel and close to 20% in term of $/area.

Finally, automotive is a compelling application for µLED which deliver the right combination of high brightness, contrast, ruggedness, and power consumption that automakers want. Cost reduction will enable µLED to enter the market, but adoption will be slow due to long design and qualification cycles.

Conclusion

While intrinsically superior to OLED in term of performance in almost all aspects, it remains to be seen if, and when µLED cost can come to a level where it can effectively compete with OLED. In the light of the recent progresses however, we no longer see µLED as a fundamental science project but more as a vast engineering and manufacturing challenge.

Many companies have some pieces of the µLED puzzle, but none have all of them. It is unlikely that any player will fully integrate all elements internally. Complex supply chain and partnership arrangements will be required to enable high volume manufacturing of consumer µLED products.

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Acronyms

AR: Augmented Reality
BOM: Bill of Material
KBD: Known Bad Die
LCOS: Liquid Crystal On Silicon
LED: Light Emitting Diode
MEMS: Micro Electro-Mechanical systems
OLED: Organic Light Emitting Diode
TFT: Thin Film Transistor