MicroLEDs Are Reaching Escape Velocity – A Focus On Transfer Processes and Equipment

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ABSTRACT

Mass transfer has long been the biggest challenging part for MicroLED.But should it be the case? In this paper we discuss what has been the latest status about mass transfer and where that puts the microLED industry: something is happening, and we explain why, with technology and market explanations.

1 Introduction

Micro-light emitting diode (microLED) 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, ideally less than 50 µm in size for consumer applications. Just like Organic Light Emitting Diodes (OLED), they offer high-contrast, high-speed, and wide viewing angles. They could also deliver a wider color gamut, much higher brightness, significantly reduced power consumption, improved lifetime, ruggedness, and environmental stability. Finally, microLEDs 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 microLED 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 microLED displays became available in 2021. However, technology, yield, cost, and supply chain issues still prevent broad adoption.

Transfer and assembly has long been the elephant in the room: unlike OLED that are built by vacuum-deposition processes over large areas, microLED requires each subpixel emitter to be transferred from a donor wafer or carrier and assembled on the display backplane. Attempting to do so with state-of-the-art pick-and-place bonding equipment used in the traditional semiconductor, LED or photonic industries would lead to throughput and cost that are not compatible with the requirements for consumer displays.

Fortunately, over the last decade, researchers have come up with various "mass transfer" solutions suitable for microLED. Some of them are now commercially available and can be purchased from reputable semiconductor and display equipment makers. Further improvement in capabilities and cost of ownership are still required though, and researchers are continuously coming up with new ideas to solve the remaining issues.

Within this paper, we would like to introduce more ideas, business related, showing the way to where the microLED is headed and where it should have to point forward, building up upon our previous presentation[1].

2 Mass Transfer Challenges

The art of making microLED displays consists of processing a bulk LED substrate into an array of microLEDs 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 microLEDs. To ensure proper interconnection and to eliminate certain image artifacts (bright or dim lines due to inconsistent spacing between groups of microLEDs), the required placement accuracy is typically ± 2µm or less. Today's best commercial 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.

	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

Tab. 1. Requirement for microLED Consumer Display Assembly

A survey of intellectual property activity indicates that mass transfer has long been and remains a major thrust area in microLED technology developments. As can be seen in Fig. 1, the CAGR between 2015 and 2020 (a 1.5 year delay is required to make sur to account for all patent applications) is up to 87%, and has been one the fastest growing activities in terms of microLED patent filing. Companies from all horizons have been identified, starting from start-ups (e.g. X-Celeprint, PlayNitride[4], etc.) to OEMs (Google, Meta, etc.).

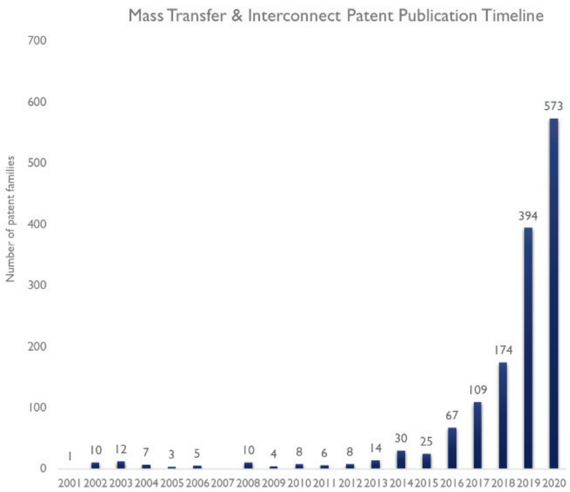


Fig. 1. Patent activity and filing timeline for microLED mass transfer and interconnections

Developing mass transfer processes with sufficient yield and throughput has long been seen as the major challenge for microLED displays. Dozens of processes have been demonstrated. We propose the classification illustrated in Fig. 2. Each technology has pros and cons, different capabilities and level of maturities[5] ranging from just concepts to tabletop experiments and, more recently, commercially available, high-volume-manufacturing-ready equipment.

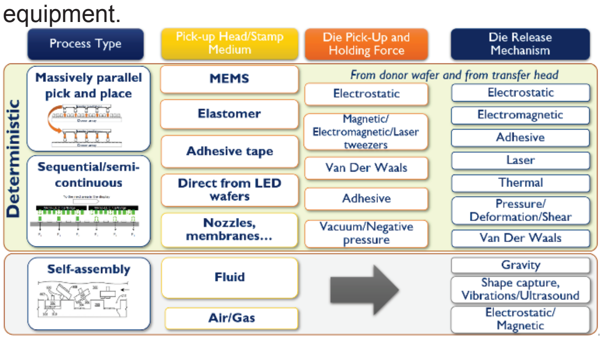


Fig. 2. Classification of mass transfer processes

However, and as we had been tracking microLED technology for many years, the big question remains: where do we stand as of today? Has a transfer assembly taken over the industry? For a microLED display assembled by mass transfer, the throughput metric that matters is the display area that can be produced per hour, i.e., the ratio of the stamp area to the equipment cycle time.

For example, an equipment with a 30x30 mm² stamp and a 20s cycle time can produce 0.16 m2 of display per hour. As of a year ago, the transfer rates of some of the major players in the industry range from ~0.2 to ~1.8 m^2/hour. As we stand, it is hard to say, definitely, that the display industry will be disrupted by such values. If we were to consider, as publicly available data, that we were to use a 25x25 up to a 75x75 mm² stamp, with around a 10s cycle time, which had been demonstrated over the past few months by several companies, anyone with be very non-convinced by the microLED disruption as it has been discussed over many years recently. But does that make this new technology irrelevant? We will briefly review the different kinds of processes for mass transfer that have been developed and then we will provide a point of view on where this will bring the industry, to illustrate the fact that everything points toward the industry as a whole reaching escape velocity, bringing microLEDs to a reality.

3 Deterministic vs. self-assembly

As of early 2022, the most popular transfer methods involve the use of polymer "stamps" (adhesive-coated or not) able to exert a pickup Alternatively, in sequential ("offset") printing, the stamp picks all the die up, and successive "prints" are made without going back to the donor after each print, until the stamp is fully depopulated. The number of times the stamp needs to travel back and be aligned to the donor to pick up microLEDs is reduced significantly. Offset printing can significantly reduce the average printing cycle time by eliminating alignment steps and reducing print-head motion. We illustrate the principle in Fig. 3.

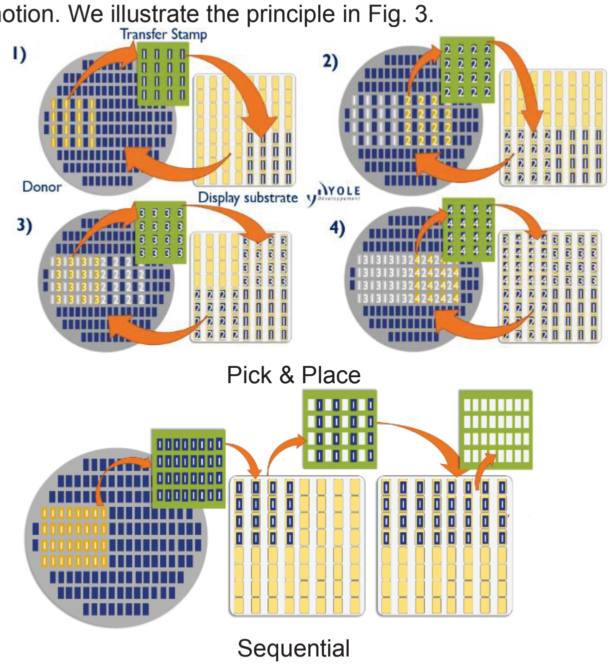


Fig. 3. "Pick and Place" (top) vs. "Sequential" (bottom) printing.

4 Throughput versus market expectations

As of today, throughputs are sufficient enough for smartphones and wearable displays, which is why we believe that as a hanging fruit, the smartwatch[6] will be the first to come consumer-oriented display revolution, likely led by Apple, leading the way towards the remaining of the display industry, as illustrated by our roadmap in Fig. 4. But as it is shown, the current status of transfer processes is not enough for other applications and major equipment players are pushing towards making these a reality. Using the example of TVs, considering an equipment that could assemble 1.8m²/hour, it would take more than 50 minutes for each color to be transferred on a regular 75” 4K TV (as we would like to remind the reader as it has been explained in previous papers, the advantage of microLEDs is that it is mostly about the resolution, not about the size; however, because stamp sizes have to be considered for assembly, and for the sake of demonstrating things we consider 75” TVs as it is bound to be the average resolution for high end TVs, segment for which microLEDs are competing).

There are many strategies to increase equipment throughput, which mainly go three ways: a) increase printhead throughput, which could bring an 8 to 12 times improvement, b) increase heads, as is done by, for example, Toray Engineering or VueReal, with the question of complexity versus reality, , which could bring a 10 to 50 times improvement, c) working with intermediate carriers (interposers) to help with die binning and pitch adjustment or re-allocation, which could also bring a several 10s of time improvement.

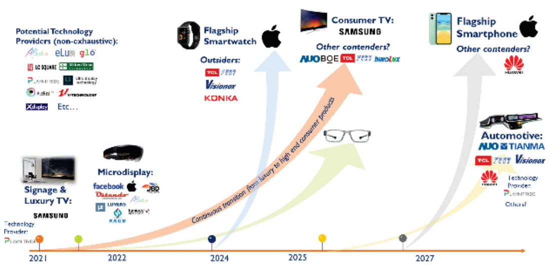


Fig. 4. Estimated timeline with leading players for microLED introduction

5 Intermediate carriers and associated advantages

This is a process that goes as follows and that is illustrated in Fig. 5. A small stamp is used to transfer the dies at high pitch from the wafer to a carrier which becomes the donor for transfer at the display pitch to the backplane with a large stamp. The strategy combines the high wafer utilization of small stamps with the reduced number of cycles of large stamps and allows binning of the “transfer fields”. Interposers can improve cost of ownership. However, they add complexity, and it remains to be seen how large a transfer stamp is possible without losing placement accuracy or affecting transfer yields.

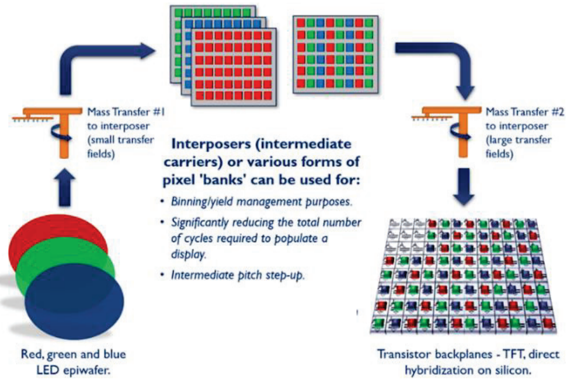


Fig. 5. Intermediate carrier process concept

In Fig. 6 we illustrate the advantage of the concept, showing that transfer cost but also wafer cost seem to be ideal; in an industry that is trying to assemble the best of three manufacturing worlds (LED, semiconductor, flat-panel displays), this looks like a very promising solution.

Type	Stamp size (mm)	# of Transfer Cycles per TV	Wafer utilization	Transfer cost	Wafer cost	Complexity
Direct transfer (1 step)	Small: $12.73 \times 12.73\ mm^2$	29,000	86%	Very high	Lowest	Medium
	Medium: $25.45 \times 25.45\ mm^2$	7326	72%	High	Medium	Medium
	Large: $101.8 \times 101.8\ mm^2$	510	64%	Medium	High	Medium
Interposer (2 steps)	Step #1: small Step #2: $207 \times 187\ mm^2$	138	86%	Low	Lowest	Higher: need to maintain placement accuracy through 2 transfer steps

Fig. 6. Transfer ideas concepts and the comparison

6 Trends in mass transfer technologies

As of today, the most mature processes are stamp-based, by MEMS, PDMS, or other solutions. Electrostatic MEMS patent activity is slowing down, probably due to Apple/LuxVue’s pioneering and strong portfolio. While suitable for small displays, cost and complexity might be an issue for large ones. There is still sizeable activity on PDMS-based transfer stamps and stretchable adhesive layers. PDMS is by far the most mature and widespread technology. Multiple commercial tools are available.

X-Display has the rights to all seminal PDMS transfer patents and the rights to license them. Few companies have so far acquired licenses as they are still exploring other technology options before moving to volume production. Process patents, such as for transfer, tend to be more difficult to enforce since the nature of the transfer process used is often not visible in the final product. Need to go to the fab to prove infringement

A fast-rising mass transfer technology has been the talk around town: laser-based. Laser-based transfer processes have been dominating patent activity for the past few years. Challenges should not be underestimated though: residue from the adhesive layers, placement accuracy for very small dies, die catching layer materials, etc. The intellectual property landscape is also becoming crowded. Nevertheless, an increasing number of companies, such as Tianma, BOE, TCL, and others, are endorsing laser processes. Coherent and 3D Micromac as well as Toray

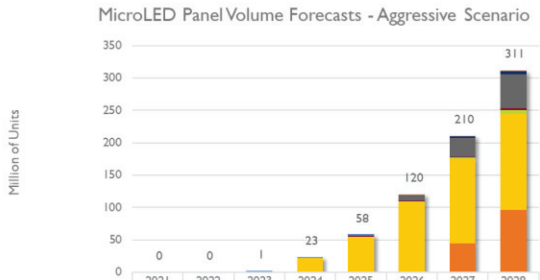
Engineering are offering commercial tools. Kulick and Soffa acquired pioneer Uniqarta. They should have miniLED transfer equipment available by the end of 2021 and microLED mass transfer in the future.

Then remain self-assembly and many other technologies. Though not as mature as the others yet, the level of creativity is impressive: although some solutions seem a bit far-fetched, inventors still come up with entirely new and original mass transfer concepts on a regular basis. But as has been illustrated in other industries and also in microLED history: there is a long way, from the lab to the fab.

7 Transfer and equipment evolutions: what it brings to the future of the microLED market

Long seen as the major roadblock for microLED, mass transfer processes and equipment have made fast progress over the last 5 years. The first commercial microLED-specific transfer tools were introduced in 2020. And in 2022, stamp and laser-based tools are available from half a dozen of reputable suppliers.

As for where the market is headed, smartwatch and AR applications will drive initial adoption. Smartphone remains very challenging and elusive. However, we are more optimistic than in our previous report: Apple's decision to push for a 200 mm microLED supply chain signals a strong will to enable the high very-small-die yields and manufacturing efficiency, as has been discussed all along this paper, which is key to achieving the cost reductions required to enable smartphone applications, make us think that this is likely. We provide in Fig. 7 what we think should happen in terms of panel volumes, considering an aggressive scenario with smartphones at the end of day, led by Apple most likely.



	2021	2022	2023	2024	2025	2026	2027	2028
Monitors	-	-	-	-	-	0.0	0.1	0.3
TVs ("luxury" + consumer)	0.00028	0.0011	0.007	0.022	0.082	0.26	0.69	1.5
Laptops	-	-	-	-	-	-	1.3	3.8
AR/MR/VR	0.002	0.01	0.3	0.6	2.3	9.6	29.7	52.7
Automotive	-	-	-	-	0.1	0.6	1.4	3.1
Tablets	-	-	-	-	-	-	1.9	5.8
Smartwatches	-	-	1.1	22.1	55.3	109.6	130.4	148.2
Smartphones	-	-	-	-	-	-	44.8	96.1
Total	0	0	1	23	58	120	210	311

Fig. 7. Projected microLED panel volumes

8 Conclusions

Until recently, a company interested in manufacturing microLED display had to develop its own mass transfer process and tools. Now, the availability of off-the-shelves tools is enabling new entrants and shortening development cycles. Many large companies however are also still developing their own processes, and, more often than not, pursuing multiple options. The key to everything for mass volume and consumer adoption is the cost. As of today, transfer solutions remain too expensive only by adopting a large size stamp can we reduce transfer processes by four. But using alternative technologies can reduce things by one order of magnitude.

At the end of the day, mass transfer is no longer considered a roadblock by most players. There are still many issues, but the industry now sees a clearer runway. Commercial availability of tools using different processes (stamp, laser) helps accelerate development (ASMPT, Amicra, Toray, Coherent / 3D-Micromac, X-Display, Shibaura). More tools are coming from TDK, V-Technology, Besi, Bolite/Contrel, and others.

However, as the idea is to target the consumer market, there is only one thing to keep in mind: strong momentum does not guarantee success: many technical and supply chain challenges could still derail microLEDs. There are still many question marks regarding yield management and display driving architecture. Cost is still 20x to 50x too high for consumer products, and cost remain the paramount idea to target these markets. Many solutions look great on paper but real-life process integration in a high volume manufacturing environment is much more challenging. We however maintain the idea of consumer introduction within the next couple of years, through smartwatches, thanks to the advances in mass transfer processes.

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