MicroLED Association

White paper:

On microLED yields, and strategies to overcome

February 2023

The MicroLED yield challenge, and strategies to overcome

By the MicroLED Industry Association

MicroLED Association

Display Yields

In the display industry, the term 'yield' generally refers to the percentage of viable or useable panels out of all the panels produced at a certain production line or fab (1). This highlights the fact that not all produced panels can be used, as some panels contain defective pixels or other problems that deem them unfit for use.

Yield is a crucial parameter for display makers, as low yields can drastically increase production costs per panel sold. In LCD and OLED production, the entire production process is performed on one large glass substrate, and producers have managed to achieve very high yields. This is seen as a major contributing factor to the affordability of LCD and OLED panels.

In the case of microLED display production, however, yield takes on a different meaning, as we will discuss in the next section.

LCDs are fabricated using a stable and mature process and LCD manufacturers reach extremely high yields. OLED manufacturing relies on less established processes, which needed time to mature and stabilize – but as of 2022 many OLED fabs have reached very high yields and it seems that one can also consider OLED production as a stable and mature process.

New OLED fabs can take a year or even longer to reach desirable yields. Recent years have shown several production lines that started to operate with a yield of around 20-30 percent, which was brought up to over 90 percent a year later (2). Stable and established fabs currently reach even higher yields than that.

The most critical stage of OLED manufacturing is probably the deposition of the organic materials, meaning the frontplane of the display. It's vital to attain precise control over the amount of deposited material and the quality of the deposition. Of course, it is also possible for other parts of the production process to damage the display, or parts of it. For instance, when phone manufacturers started using displays with holes in them for camera (and other) sensors - be it notch or hole type - complication arose in the production process and display prices were estimated to go up by around 25 percent due to lower yields (3).

It is important to understand how the size of a display effects the yield. If it can be said that for each given display size (1 square inch, for example) there is a certain chance of a defective part (like a bad pixel) - than it is logical that the bigger a display is, the more chance it stands to contain defective parts. In the below example, a certain substrate had 2 defective regions. The process created 24 displays in total, so the yield is 22/24 or 91.66 percent.

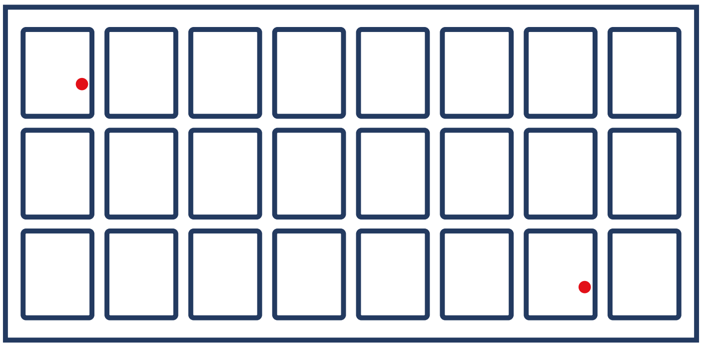


Figure 1: Substrate with 24 displays, and 2 defective regions

The second example shows the same substrate with the same defective regions. Only in this case, 3 larger displays were fabricated. The yield here is only 33.33 percent:

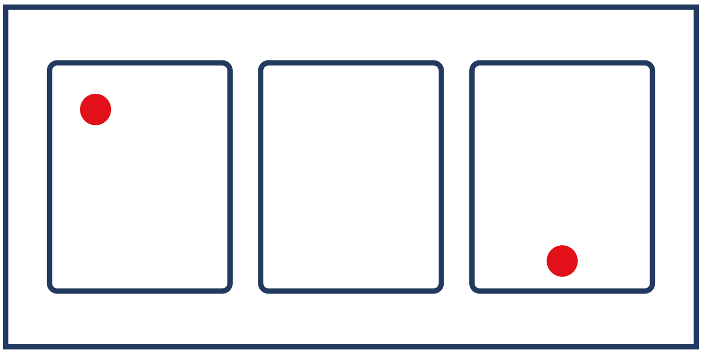


Figure 2: Substrate with 3 displays, and 2 defective regions

MicroLED Production Yields

The process for MicroLED production is different than that of LCDs an OLEDs (4). The main difference is that it consists of two separate tracks: backplane production, and LED production, with the LEDs then transferred onto the backplane.

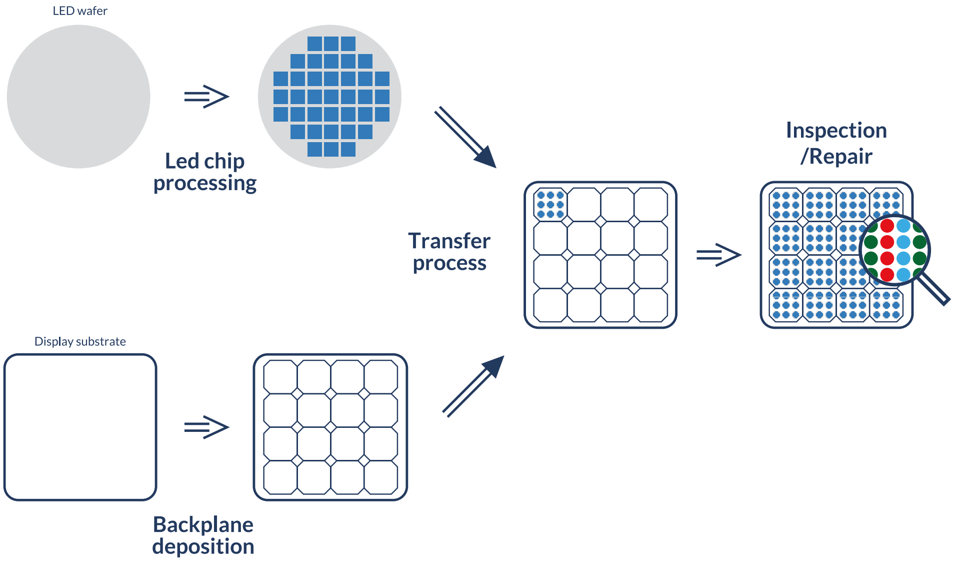


Figure 3: Simplified microLED production process

This means that there are also two different production yields in microLED Production:

* LED production and processing yields
* Transfer process yields

Backplane production, assuming it is based on traditional backplane production approaches (LTPS, Oxide-TFT), is a mature process, is out of the scope of this white paper.

A MicroLED display may include millions of individual LEDs. A 4K display has over 24 million subpixels, and an 8K display contains around 100 million subpixels. This means that even at very high yields, defective LEDs will not be avoided. At 99.99999% yields, there will still be about two defective LEDs in each 4K display.

It is important to note that MicroLED quality relies on the consistent output of individual light-emitting subpixels. Inconsistencies in microLED brightness or color, any inaccuracies during the placement process, and any other process problems can result in displays with a noticeable non-uniform, mura or speckled appearance.

MicroLED chip makers will have to be able to identify defective LEDs and adapt the transfer process. With transfer process defects, unless we reach almost 100% yield, producers will have to rely on a repair process, or LED redundancy. These strategies will be discussed later in this white paper.

Note that there are different types of MicroLED displays and production methods. It is too early to determine which of the approaches will indeed mature into mass production, and the industry may adopt more than one production method and display type. However, when discussing yields, it is vital to define the specific type of display and the production technology. Several types of displays and architectures will be mentioned here, to demonstrate the complexity of the issue.

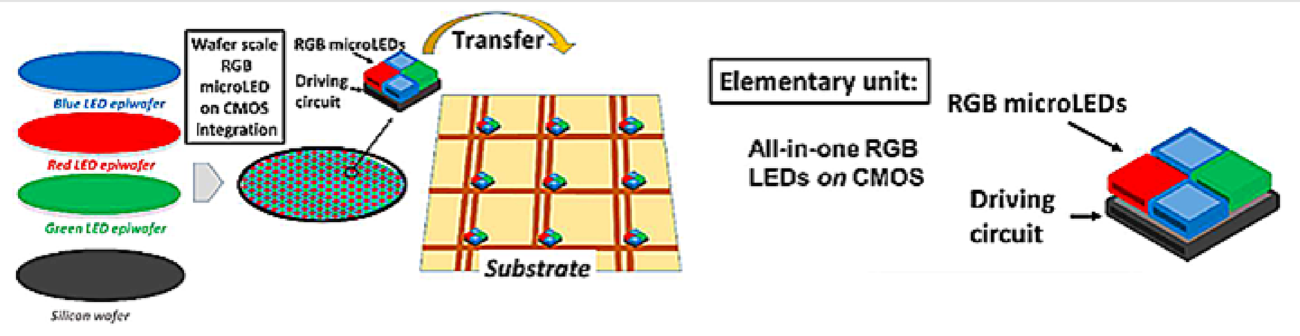
Microdisplays are small displays (usually 1 inch and under) with very high pixel density, especially appropriate for near eye applications like AR headsets or rifle sights. MicroLED technology, with its high brightness and efficiency, is very promising for such applications. In microdisplays, the backplane is made of Silicon CMOS which grants significant performance advantages. The small size of these displays enables unique microLED production methods. Some companies endorse the use of a monolithic process, in which the LED deposition is done directly on a silicon wafer. This means that there's no need for a transfer process. A monolithic approach is only suitable for microdisplays, though.

PM-μLED: passive matrix (PM) displays are simple displays controlled by a simple backplane. In PM displays only one line of pixels is lit at a given time. This means that there's no need for the pixels to "remember" their status while updating another line - as all the other pixels are turned off. This means that these displays are simple to produce, but there are severe limitations on resolution, efficiency and lifetime (due to the need for extra strong pixel intensity to make up for the time when they are off). In any case, these displays contain a relatively small amounts of pixels, which makes microLED adoption relatively easy. Possible applications are fitness band displays, industrial displays, automotive HVAC displays, and others.

TFT AM-μLED: AMLCD and AMOLED displays all use high end TFTs which enable the production of high performing and high-resolution displays. The two main backplane technologies in use today are LTPS or Oxide-

TFT, and this is likely to continue for TFT MicroLED displays as well. MicroLED backplane is rather similar to what is currently in use for OLED displays, however in some MicroLED displays there are even more substantial demands of the backplane than in OLEDs (5).

PCB microLED: In these displays, the control over single LEDs is done using a PCB rather than TFTs. PCBs seem to be mainly appropriate for large display solutions, which are made from small tiles. The first ultra large MicroLED displays (by Sony, Samsung, and others) were indeed PCB-based, but generally this does not appear to be a suitable long-term solution and the industry is moving towards TFT-based solutions and other methods.
Tiled microLED: One of the major advantages of MicroLED technology is the possibility of making them completely bezel-free (6), putting two such bezel-free displays together creates a totally seamless display. Beyond the advantage of production flexibility, this also has a distinct yield advantage, as all displays are created from relatively small parts as was shown in Figures 1 and 2.



MicroIC MicroLED display production (CEA-Leti)

MicroICs: In this architecture, small components are made that include the LEDs (one or more pixels) and a tiny circuit that controls them. The entire LED+circuit component is transferred to the final display. This is an interesting method and one of its advantages is that a defective LED and circuit component can be replaced by a functioning one. This h that the transfer process from the LED epiwafer to the component has a high yield. On the other hand, there is also a need to transfer the MicroIC Engine to the final display - which can also cause problems...

LED Production Yield and Challenges

LEDs are manufactured through a complicated process, that includes two main stages. The first is creating the LED epiwafer, done by evaporating materials onto the substrate. The second stage is called chip processing, in which the LED production is finished (adding electrodes etc.) and also performing chip singulation – which means dicing the LEDs into individual chips, and finalizing all interfaces or connectors. In both these stages, the process is not 100% foolproof and so some of the LEDs will not function as required.

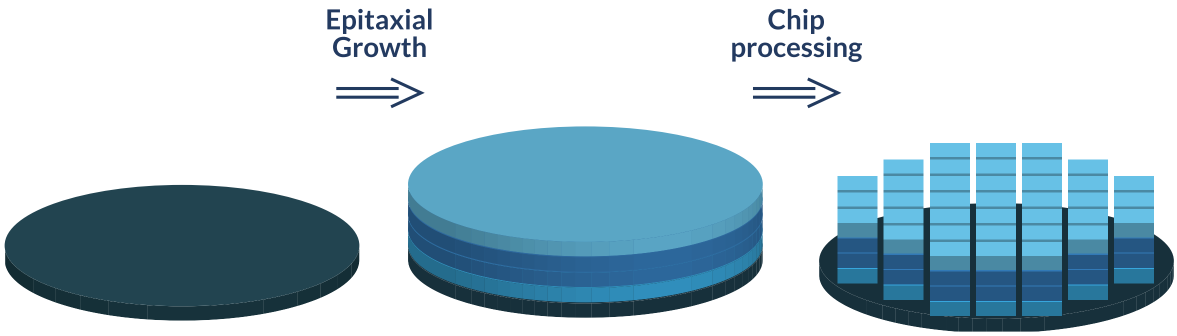


Figure 5: simplified LED production process

During the production of the epiwafer LED stack, some parts of the wafer may not be properly formed, causing the stack to come out defective. For instance, segments close to the wafer's edge tend to be more prone to problems (see image below, which shows the usable parts of a specific wafer).

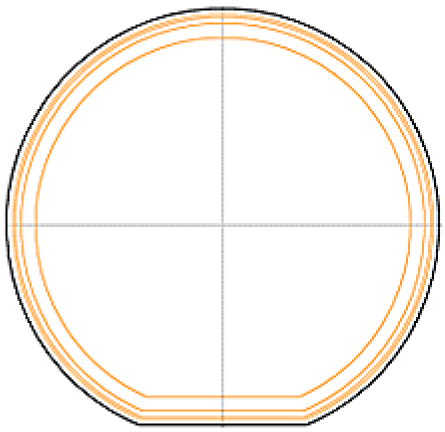


Figure 6: Sample wafer with marks showing the usable area

In some cases, a part of the LED stack will not be perfectly deposited, in a way that will make the LED usable, but with some performance issues - for example the LEDs will emit a different color than planned or have less-than-optimal efficiency. These are, of course, issues that must be dealt with.

In the chip processing stage, some of the LEDs can be damaged - and these LEDs will either be completely defective or may suffer from non-optical performance (as was discussed above).

Yield problems at this stage have two main consequences.

First, an inspection process should be performed to identify problematic areas and defective LEDs. Since every wafer can have hundreds of millions of LEDs (depending on wafer size and LED size), this is by no means a simple process, which can take a long time and dramatically increase production costs. At the end of this process, problematic LEDs should be tagged (or highlighted for future treatment) or binned (sorted by performance).

Another consequence of errors during LED creation is, of course, cost. Any unusable LED brings up the cost of overall production. The higher yields are, the lower the final cost of the display production is. We will discuss transfer process technologies later in the white paper.

Making LEDs for lighting applications is easier because at the end of the LED creation process, every LED is treated as a single device. This means, for example, that less-efficient LEDs can be used for less demanding or lower-cost applications. However, in the mass transfer process, a large number of LEDs are transferred in parallel, which complicates things. The integration between the LED inspection process and the transfer process is crucial.

Transfer Process Yield

The transfer process can also suffer from various problems. Some of the LEDs could be damaged (especially when they are physically handled in order to transfer them), or they could by placed in the wrong location.

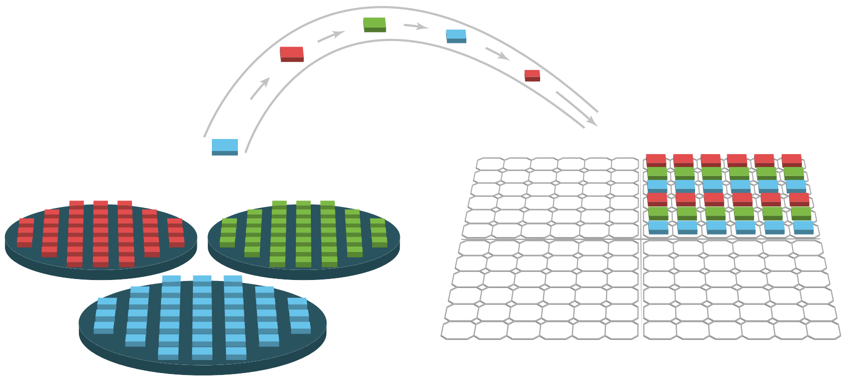


Figure 7: Simplified microLED transfer process

Unlike standard LED production that is a mature process (8), microLED transfer process development is still at an early stage, and standard LED placement and bonding processes are not adequate. The most popular microLED mass transfer processes are based on stamp transfer, that uses a print head to pick up several LEDs from the wafer, transfer them to the substrate, and release them. This mechanical handling of LEDs is relatively straightforward but could potentially harm the chips.

There are many other transfer process technologies being developed and commercialized today, each with its own implications on yield. We will discuss some of these processes below.

MicroLED Yields - Strategies to Overcome the Challenges

Generally speaking, there are two main strategies that companies should employ to help overcome yield issues:

1. Improve the yields of production: higher quality LED fabrication, better compatibility to transfer processes, implementing efficient and accurate transfer process, etc.
2. Introduce mitigation procedures: even with better production, it is likely that it won't be possible to create 100% safe processes. Companies will have to use inspection and repair processes to fix the yield problems and enable defect-free displays. Another possible solution explored by display makers is LED redundancy.

Improving the quality of LED production processes results in better yields, which is, of course, highly desirable. A major improvement can be obtained via more precise production - by improving the clean-rooms, using precision tools and adopting higher-end materials. Methods that are more compatible with producing LEDs of extremely small sizes should also be considered.

At the individual LED level, luminance and color output must be precisely measured, and high-end inspection and characterization tools are required to assess performance and uniformity down to the subpixel level.

Following the LED production process, the first step in mitigating yield issues is to identify faulty LEDs, and this is where a quick and efficient inspection process is the key to precise identification and tagging. Once the faulty LEDs are identified, it's vital to make sure that the transfer process will not use these LEDs. This depends on the transfer process itself - does it allow skipping unwanted LEDs? The transfer process is a very complicated and critical stage.

During the transfer stage, there is a possibility that the LEDs will be damaged or misplaced. After the transfer process the first step is to inspect all LEDs and make sure they can function. As was already mentioned, achieving 100% yield is highly challenging.

It is important to note that in some cases problematic LEDs can be corrected rather than rejected and replaced. By addressing and compensating specific pixels, makers can retain high quality images over the whole display, improve luminance uniformity and correct color issues.

In this document we discussed inspection and repair (or rejection) at several stages. Display makers also have the option of disregarding defective LEDs in the process and doing an inspection & repair step only at the end of the production process. This simplifies the production line and may offer faster throughput. It is too early to tell which solution (multiple repair steps or a single one) will be adopted by display makers.

MicroLED Industry Association member technologies

The high interest in MicroLED-based display solutions and the many technical challenges that the industry faces spurred many companies to develop solutions that aim to improve the yield problem. In this section we will list some technologies and solutions developed by MicroLED Industry Association members.

3D-Micromac - UV laser microLED production systems

Germany-based 3D-Micromac AG is the industry leader in laser micromachining. For MicroLED display manufacturing, the company offers innovative and enabling laser solutions for industrial mass production. This includes:

* Laser-Induced Forward Transfer (LIFT) which enables the transfer of hundreds of millions of MicroLEDs without having to apply mechanical forces
* Laser Lift-Off (LLO) which guarantees a highly uniform, force-free lift-off of different layers on wafer and panel substrates

* Repair/Trimming : Single die repair process at every step of the MicroLED production process, thus helping to mitigate the yield problem and make sure displays are defect-free. The company's laser tools can be used to remove defective LEDs from the display, and to insert good LEDs instead.

3D-Micromac's mass production systems are based on proven UV laser technology, both on DPSS and excimer laser sources.

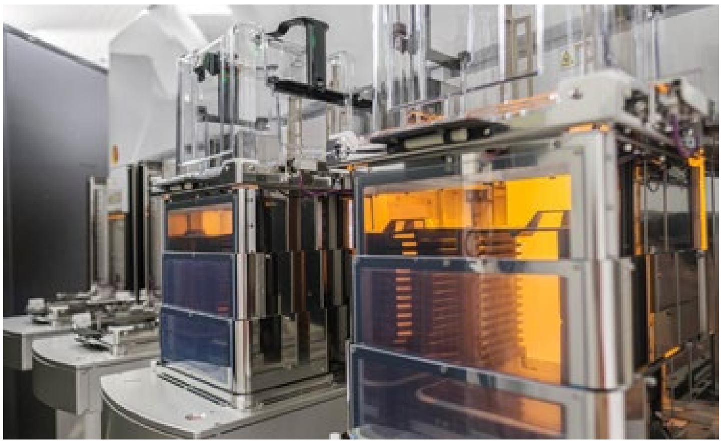


Image 8: microMIRA high throughput LLO system

3D-Micromac is a pioneer in the field of MicroLED manufacturing, with more than 10 laser processing systems sold to date for MicroLED applications, including a recent order for multiple microMIRA systems from a leading optical solutions provider.

ASMPT – Mass transfer & mass bonding equipment for MicroLED production

Globally headquartered in Singapore, ASMPT is a leading global supplier of a wide range of hardware and software solutions for semiconductors and electronics production. For the MicroLED industry, ASMPT provides mass transfer & mass bonding equipment for MicroLED production and works closely with Tier-1 microLED display makers.

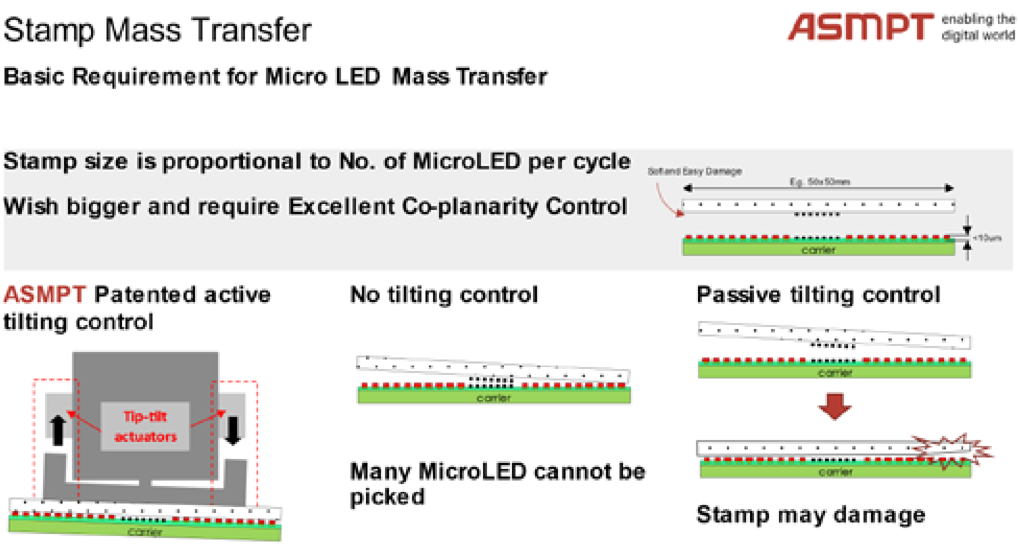


Figure 8: ASMPT active-tilting stamp head device

ASMPT developed several innovative technologies to increase microLED production yields. For mass transfer processes, for example, ASMPT developed (and patented) an active tilting control device. The company explains that it is vital to control the tilt of the pick tool, as if it and the substrate aren't completely coplanar, some microLEDs cannot be picked up. Some companies use passive tilting control, but this can damage the pick tool or the MicroLEDs as the tilts happens after the pick tool is in contact with the LED wafer.

Other solutions from ASMPT include the AD300Pro Bonding machine that can support bonding with a wide range of force options - from 0.01 to 50 kgf. This is required for high yield operation, as a large bonding force is needed when picking up the LEDs, but while transferring it, the small and weak pick tool needs extremely small force so it is not damaged.

ASMPT also offers chip scanning and cleaning processes, that together increase yields and enhanced the microLED transfer process.

CEA-Leti – Smart Pixels

Researchers at France's CEA-Leti have developed a unique approach to combine microLEDs and micro-ICs into so-called Smart-Pixels. This technology offers several advantages to microLED display fabrication, and also have a unique advantage to help mitigate production yields.

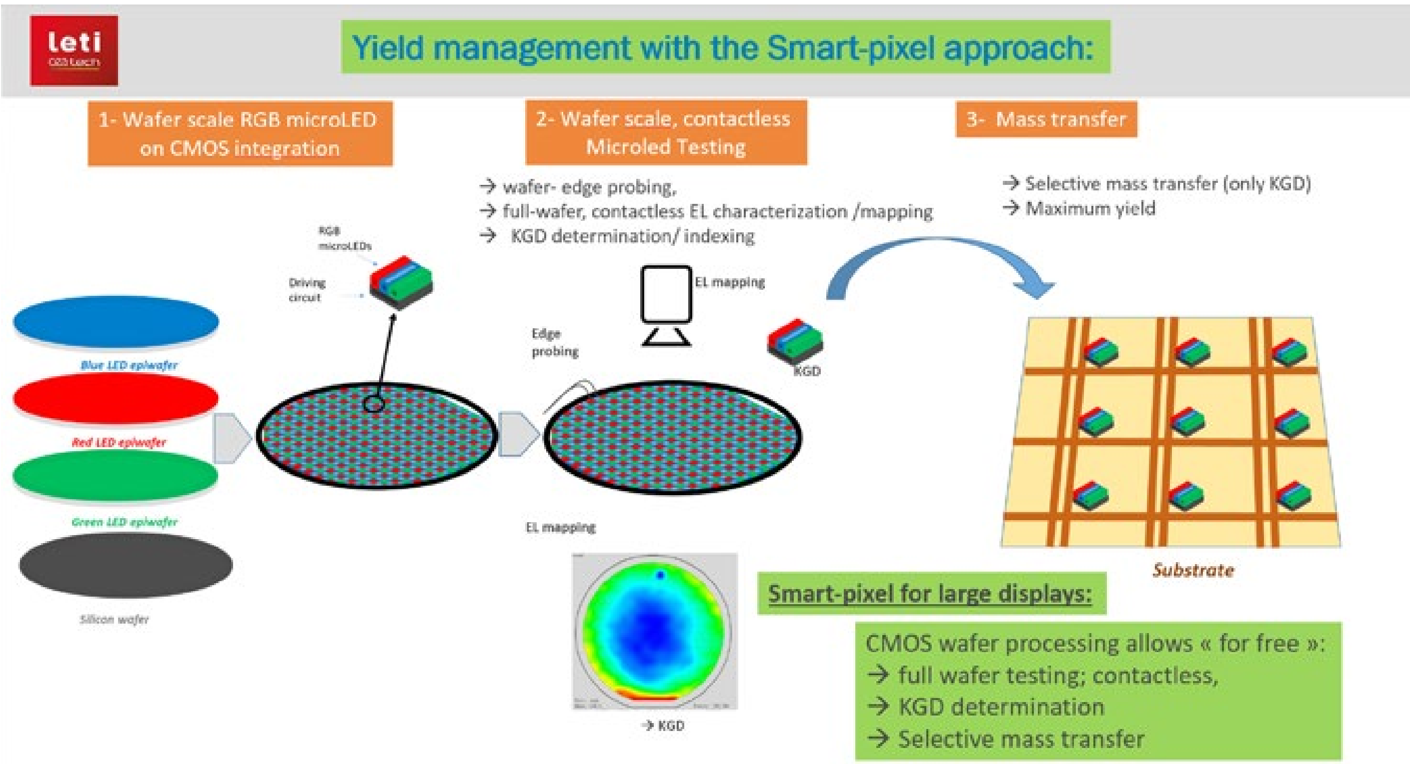


Figure 10: CEA Leti Smart-Pixel approach

Smart-Pixels include a CMOS micro-IC. Following the fabrication of each unit, it is straightforward to test and evaluate the LEDs ,using for example contact-less EL mapping. Using a selective mass transfer, it is possible to only transfer only known good dies.

Coherent - laser tools for microLED processing

Germany-based Coherent offers laser components and laser-based systems to many industries. The company is a leader in lasers used in the display industry. Coherent says that lasers are highly suitable for microLED processing and production, and can help overcome the poor yields associated in other processes. Lasers can be used in several microLED processes and steps:

* LLO, or Laser Lift-Off (7)
* LIFT, or Laser Induced Forward Transfer (7)
* Excimer Laser Annealing (ELA) to fabricate a LTPS-TFT backplanes
* Laser cutting at different levels of aggregation
* Laser-based microLED repair

Excimer lasers (used in LLO, LIFT and ELA processes) have excellent potential for emerging laser applications in the microLED industry. Their characteristics such as short UV wavelength, and short pulse length, combined with high energy and power, are well suited for the III-V material systems commonly used in LED manufacturing. Coherent says that its latest lasers enable significantly differentiated process strategies that are highly productive, and therefore cost effective.

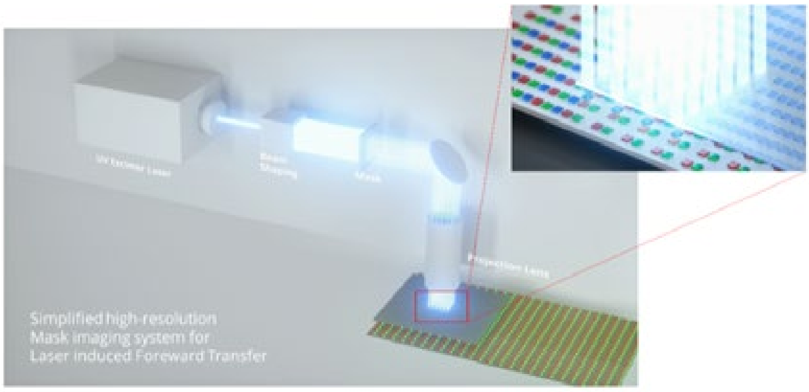


Figure 11: short wavelength UV laser and a photomask create a multiplex process

Coherent explains that one unique advantage of its short wavelength UV light laser is that its large pulse energy can offer a multiplex process advantage, as the beam can be used to project a photomask (see image above) and thus enable to process hundreds or even thousands of LEDs with each pulse.

Comptek – high quality LED sidewall passivation

Comptek Solutions has developed a unique approach to overcome the detrimental sidewall defect issue in microLED manufacturing with state-of-the-art atomic level surface engineering processes. Comptek's patented technology transforms the LED surface into high-quality crystalline oxides with a low density of defects.

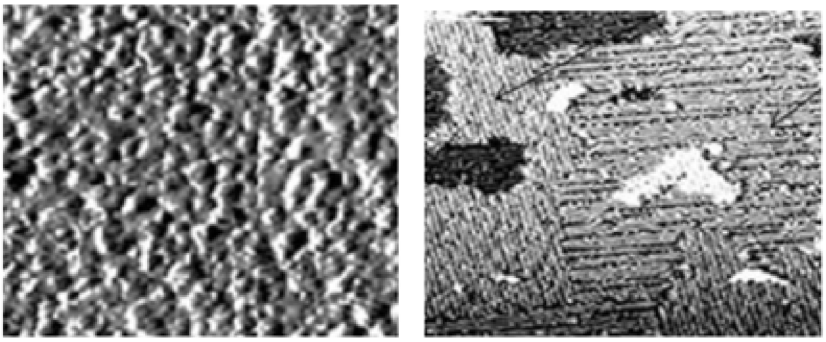


Figure 12: Scanning Tunneling Microscope image from native oxide III-V surface vs. crystalline oxide III-V surface formed with Comptek's technology

Using Comptek's technology, it is possible to reduce the microLED die size with a lower rate of efficiency loss. The company reports that a 5 um LED will suffer less than 20% reduction in efficiency compared to 80 um chips (without the passivation, such a size decrease will results in ~70% efficiency drop).

Comptek's technology also assist to mitigate yield issues. Beyond the fact that it helps reducing microLED chip sizes which helps to improve yields, it also significantly improves chip to chip uniformity and homogeneity within each wafer. It can also reduce the number of defective LEDs on the wafer.

eLux – fluidic mass transfer processs

eLux Inc. was established in 2016 in the USA as a spin-out from Sharp Labs of America. eLux developed a massively-parallel fluidic microLED assembly process. eLux's process (amongst its other benefits) has some major advantages when considering display yields.

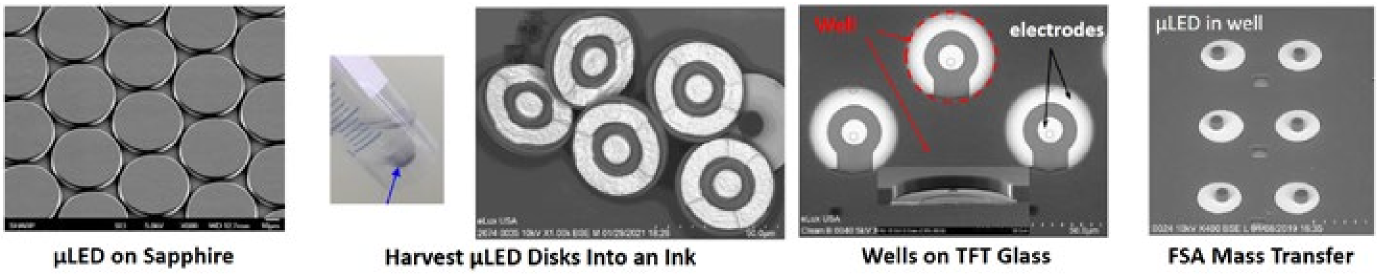


Figure 13: eLux fluidic process, from microLEDs on a wafer (left) to microLED display array (right)

As was discussed above, following the epiwafers and chip processing stages, it is vital to identify and remove defective LEDs. Most transfer process are based on a stamp, which means that the removed LEDs create gaps in the resulting displays which needs to be fixed by adding replacement microLEDs, which can be a time-consuming process.

eLux's fluidic process uses a selective harvest process, which traps defective devices on the carrier, preventing them to enter the microLED ink. The resulting ink contains only known-good-die, which are then used to create defect-free displays.

Another advantage of the fluidic process is that it randomizes the LEDs. Many times, when LEDs are grown on the wafer, entire areas may suffer from slight changes to emission spectrum (wavelength) or brightness. These are still usable LEDs, but when grouped together on the display, they create pattern non-uniformity (mura) which is highly undesirable. The randomized fluidic process eliminate this noise and creates higher quality displays.

Inziv – PL, EL and Nano-optical measurement systems

Israel-based InZiv developed a unique measurement tool specifically developed for microLED inspection. The InZiv solution integrates PL, EL and nano-optical measurement, all in one platform.

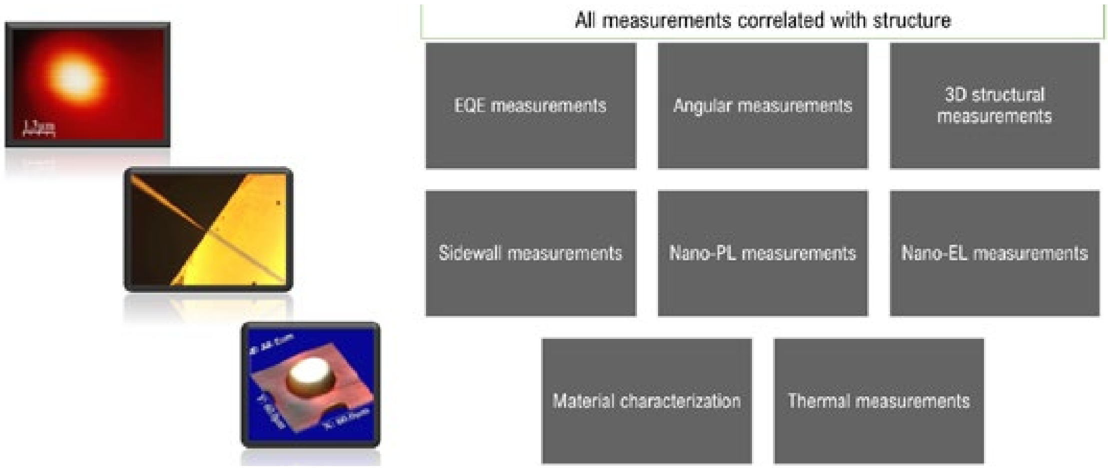


Figure 14: InZiv's measurement platform

The InZiv platform supports a wide range of wafer sizes, it has an integrated Big Data & AI platforms, and can be scaled-up to use from R&D systems to production systems. InZiv says it tools offer the highest electrical and optical sensitivity ranges in the industry.

InZiv's tool is highly effective to overcome yield problems with epiwafer deposition. The combination of the three inspection methods enables to quickly identify problematic areas on the wafer followed by highly detailed inspection of specific LEDs to correctly tag (bin) problematic chips.

QustomDot – cadmium free quantum dots technology for microLED displays

Belgium-based QustomDot is an early stage company that develops cadmium-free quantum dots for the microLED industry. QustomDot combines unique QD synthesis, surface engineering and ink/photoresist formulation into patterned color conversion layers for microLED displays.

Using QDs allows display makers to adopt an architecture that has only blue LEDs. This has many implications – one of them being that it increases transfer production yields.

If the blue LEDs are transferred to the display substrate before color conversion, then the transfer process is simpler as it handles single LED types and is easier to optimize and thus higher than transferring blue, red and green LEDs. The inkjet printing of QDs over microLEDs has very little effect on yields, as this process can be optimized to reach almost 100% reliability.

Producers can also choose to deposit the quantum dots on the original blue LED wafer, thus creating RGB LEDs on a single wafer. These LEDs can then be transferred as complete pixels (red, green and blue) in one transfer step, which again increases yields compared to standard processes which has to perform three transfer steps, one for each LED (as these originate from different wafers).

Radiant – advanced microLED imaging systems

US-based Radiant Vision Systems, a Konica Minolta company, provides advanced imaging systems to critically evaluate light, color, manufacturing integrity, and surface quality of illuminated displays and device assemblies. The company offers fully customized and automated inspection systems for microLED development and production processes.

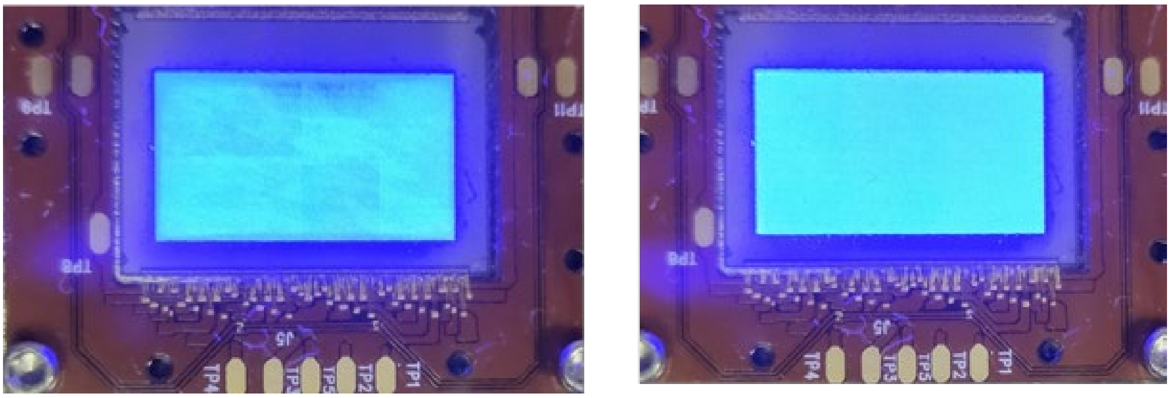


Figure 15: a microLED microdisplay panel, by Jasper Display, before (left) and after (right) demura correction using Radiant's ProMetric and TrueTest solutions.

Radiant offers solutions and methods to address quality control at critical points in the microLED fabrication process. To provide wafer-level inspection of microLED chips, a ProMetric imaging photometer or colorimeter can be used with an objective microscope lens to magnify microLED subpixels at extreme details in a measurement image and identify defects. For panel-level inspection Radiant has developed two patented methods via its TrueTest software.

Radiant's solution can accurately quantify individual subpixel brightness and color and compute specific correction factors. Together these two tools can be used to identify and correct mura issues in microLED displays. This process, called 'demura", results in a better display image quality by improved luminance uniformity and correct color across the display (see figure 15 above for an example).

Terecircuits - transfer material for efficient LIFT processes

US-based Terecircuits believes that future microLED transfer processes will be based on laser processing such as LLO and LIFT (7). The company developed a transfer material that was specifically engineered for a LIFT microLED process. The film offers several advantages – for example it requires a lower activation energy than other materials, and so a lower-cost laser can be used. Terecircuits' technology can use masks that enables easier positioning.

In fact, Terecircuit's patterned masks can be used to save precious time when dealing with known defects on microLEDs die on the epiwafers. In addition, the company suggests using a special defect-mask that can be used to first remove the known-bad-dies (KBD) from the wafer, and then continue to move the known-good-dies (KGD) from the wafer to the substrate or donor film. This technology can greatly dimmish the challenge of low epiwafers and chip yields which is especially useful in this early stage of the industry when the yields are low.

VueReal – microSolid printing technology

Canada-based VueReal is a startup company that develops Micro-LED display technologies. VueReal developed a cartridge-based microLED printing process that can produce high density displays at high production yields.

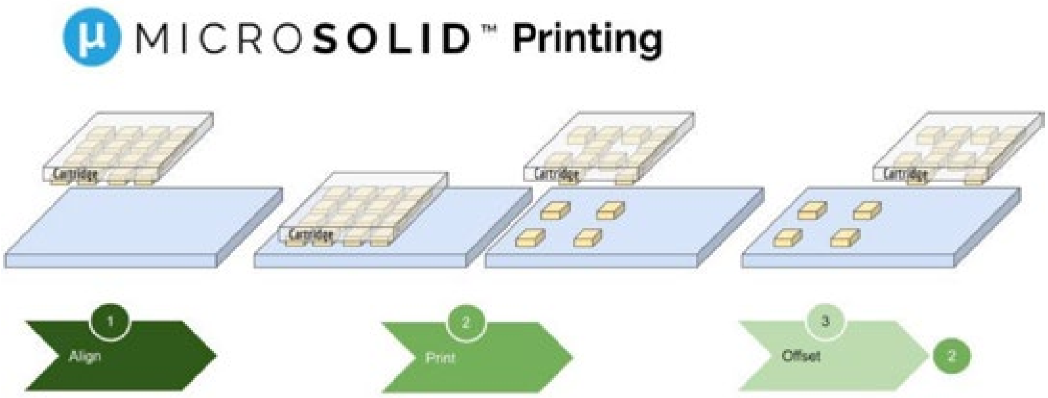


Figure 16: VueReal's microsolid printing process

The company's microSolid printing process can decouple yield, uniformity and throughput issues in the transfer process. The basic idea is to use prefabricated cartridges filled with microLED to offset and print a substrate. The cartridges can be inspected for performance and defects before transferring and binned for better display uniformity. By splitting the transfer process into these two distinct process, the company reports an increase in operational yield, and higher production throughputs.

VueReal also developed a self-aligned bonding process, that is based on its microSolid printing. This bonding process enables higher resolution displays (suitable for AR/VR applications) and also enables VueReal to adopt a die-to-wafer bonding process thus eliminating the mismatch between the backplane and microLED wafer size and material.

Footnotes

(1) The term yield is sometimes also used to note the area percentage of a glass substrate that is used for display production (the other percentage is 'dead' area). Yields are also sometimes (but not often) used to denote the utilization rate of a display fab (i.e. how much capacity is actually being produced compared to the whole potential capacity if the produces panels at all times).

(2) According to reports, when Samsung started selling QD-OLED displays in early 2022, their yields were 20-30 percent. A few months later, the Company managed to stabilize the process and reached a 75 percent yield, which became 85 percent around August 2022. See: https://www.thelec.net/news/articleView.html?idxno=4174

(3) https://www.oled-info.com/ihs-notch-type-oleds-cost-25-higher-regular-oleds-due-yield-loss

(4) This is true for almost all display types, but could be different for MicroLED Microdisplays (see discussion above).

(5) The main problem in the MicroLED field is the fact that in order to reach high performance, the red LEDs are made from a different material than the blue and green LEDs. This means that the different sub pixels behave differently, which makes controlling them more complicated - the current required to increase brightness by a certain degree can be different, for example. This is a major issue, which will require complicated changes to the backplane - which can affect yields when making the backplane. Other solutions to this problem include the use of only blue LEDs coupled with color conversion to red and green, or manufacturing native red LEDs using GaN materials or 3D Nanowires. Recent years have brought great progress in all above-mentioned solutions.

(6) This is impossible in OLED displays, as the display has to be protected via encapsulation to prevent the entrance of air and water.

(7) LLO stands for Laser Lift Off, which is an existing technique used to remove microLED dies from the original epiwafers using an excimer laser. LIFT, or Laser-Induced Forward Transfer, is a different technology used to move LEDs from a donor film to the final display substrate.

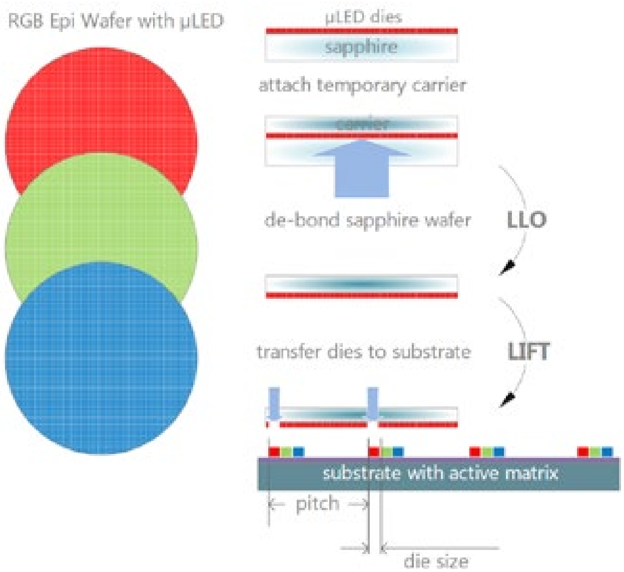


Figure 17: LLO and LIFT laser processes

The figure above shows a schematic of how LLO and LIFT are both used to transfer LEDs from epiwafers to a donor-film and them from the donor to the final display substrate (source: Coherent)

(8) While it is true that LED production is mature, the processes still need to be updated and refined for microLED production, which can drastically effect the yields and implications