# Trends Toward Integrated RGB Microsystems for Mini and MicroLEDs: MicroLED in Package and Smart Pixels

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Keywords: MiniLEd, MicroLED, QNED, OLED, Inkjet.

## ABSTRACT

*MicroLEDs promise new generations of displays with improved performance in brightness, energy efficiency contrast, color gamut etc. Yet, despite all its promises, the adoption of microLED technologies remains anecdotal. This paper will discuss how integrated microLED microsystem (MicroLED in Packages, Smart Pixels) could accelerate adoption by reducing assembly, testing and yield management costs while improving performance.*

## 1 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 microLED display 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 2022 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.

## 2 Technical challenges for MicroLED Displays

### 2.1 Overview

MicroLED technologies have made spectacular progress on all fronts over the last few years. MicroLED exists at the intersection of the traditional TFT display, LED and semiconductor industries. MicroLED can therefore rely on a lot of technology bricks and equipment developed for those industry. There are however some unique challenges related to microLED manufacturing and display integration. Figure 1 summarizes some of the key technology challenges that still need to be solved to enable broader microLED adoption in consumer displays [1]. Some of those challenges that are especially relevant to the integrated RGB microsystems are discussed in more details in this section below.

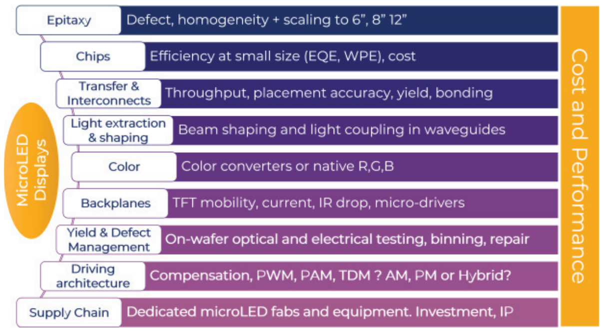



**Fig. 1 MicroLED Challenges**

### 2.2 Mass transfer

MicroLED transfer and assembly require processes and equipment that can assemble hundreds of millions of microLED per hour, about 5 orders of magnitude faster than existing high precision die bonder.

| | 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 million die /hour |

**Table. 1 Mass transfer requirement**

Transferring the chips onto the backplane is only one part of problem. MicroLED's small size brings new challenges in term of interconnects to ensure high conductivity and robust mechanical attachment to bonding pads that can be as small 3 x 3 μm$^2$. In addition, to prepare the bonding pads on the display substrate, commonly used screen printing or electroplating technics could lack the required accuracy. Lithography or e-beam metal deposition are capable but expensive alternatives.

Progress in mass transfer over the last 5 years has been spectacular, to the point that, as of late 2022, many industry players no longer see it as a fundamental roadblock. Off-the-shelves mass transfer equipment are now available from more a dozen companies. While still imperfect, many are sufficient for development purpose or even for pilot lines and first products. The availability of those tools significantly lowers barriers of entry and shortens development cycles. Nevertheless, further improvement is needed to produce high yield, high throughput cost-effective consumer displays.

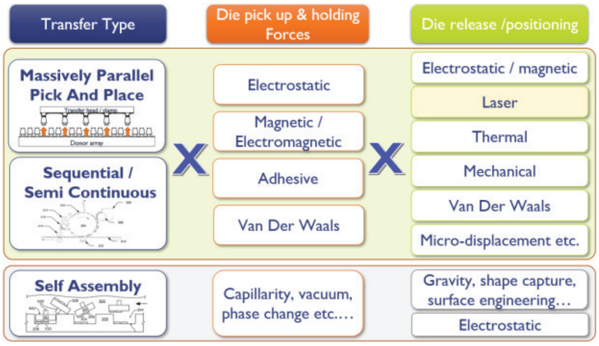



**Fig. 2 Overview and classification of the various type of mass transfer processes**

### 2.3 Yield Management: inspection, testing, binning and repair.

A major challenge for microLED display manufacturers is defect management. In modern displays, defective pixels are no longer acceptable. 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 2022, this remains the LED chip. Defects can occur at the epitaxy level, with particles originating from the environment, the substrate, or the reactor. However, most stem from the subsequent lithography, etching and deposition steps needed to form the microLED chip.

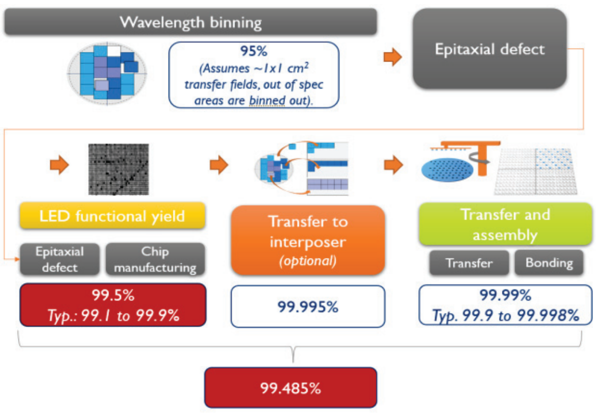



**Fig. 3 MicroLED Process Flow and major yield contributors**

A 99.485% yield on an 8K TV (100 million chips) still means that about half a million pixels will be defective and need repair. Because defects are randomly distributed across the display, they must be repaired individually (one repair step per defect). Repair cost can therefore easily exceed that of the initial assembly. The industry is striving to reduce this number and is 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.

Inspection, metrology, and functional testing are the cornerstone of efficient yield management strategies. Automated Optical Inspection (AOI) and photoluminescence are often combined to identify defective die. Photoluminescence can be easily and efficiently performed at the wafer-level. Combined with AOI, it provides a first level of information regarding defective die. Photoluminescence however leads to a lot of false positive: because the signal from the LED is obtained by contactless, optical excitation of the active emitting region of the LEDs, it often misses electrical defects such as shorts etc. [2]

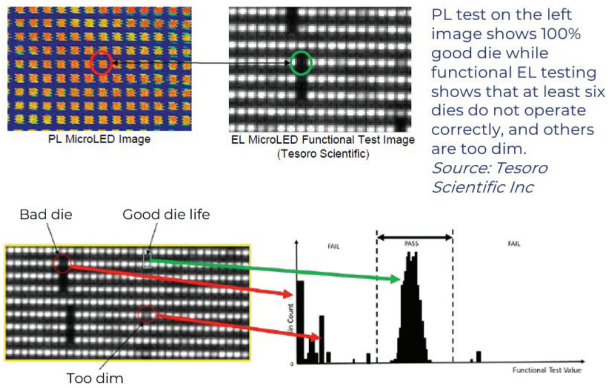



**Fig. 4 Overview and classification of the various type of mass transfer processes (source: Tesoro Scientific)**

100 percent, wafer-level functional testing would be desirable to see how the microLEDs perform under electrical excitation and to gather, for each die, information such as voltage, brightness, leakage etc. This is however very challenging to do with microLEDs. Due to the vast numbers (up to 100's of millions) chips present on each wafer, traditional probe testing is not cost effective (low throughput per wafer) and the metal probes could easily damage the small contact pads on the microLEDs die. Various equipment manufacturers are developing alternatives to adapt probe testing to the specific challenges of microLED, using for example, MEMS-based conformable probe cards. Some envision prob testing by the mas transfer head. Efforts are also

ongoing to develop massively parallel, contactless testing methods and equipment based on concepts often derived from TFT array testing.

### 2.4 MicroLED Display Cost.

Depending on the application, microLED display cost is still 20x to 50x too high to pretend addressing real consumer products. The challenge appears daunting, but LCD cost decreased 300x, from $30k/m$^2$ to $100/m$^2$ in 25 years. The situation is different for microLED 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, microLED 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. Especially, adoption of 200 mm or 300 mm could unlock access to a vast array of mature, cost-effective semiconductor manufacturing tools capable of delivering high throughput, high yields and with more advanced capabilities compared to traditional LED manufacturing.

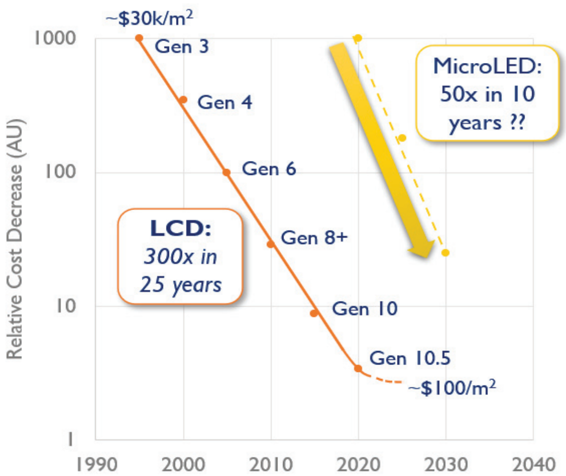


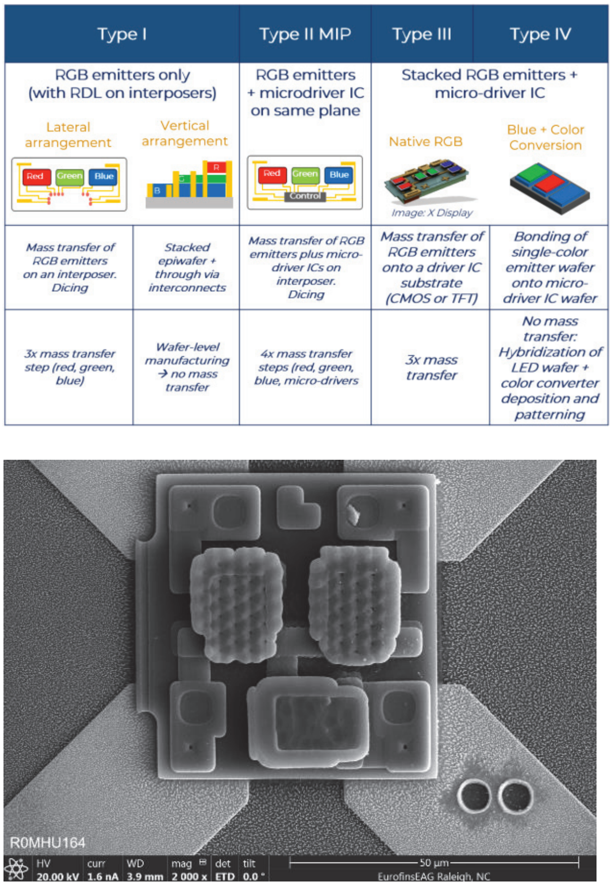

**Fig. 5 LCD vs. microLED cost reduction trends**

## 3 MicroLED in Package (MIP) and smart pixels

### 3.1 Overview of architectures

The most common microLED display architecture relies on Chip-On-Board (COB) architectures where each individual microLED chip is bonded directly onto the display substrate (TFT backplane, CMOS backplane or Glass Circuit Board). For a typical Flip-Chip architecture where both anodes and cathodes are on the same side of the chip, this means 2 bonding pads per LED. For vertical LEDs with one electrode on the bottom and the other on the bottom, this implies a bonding pad on the substrate for each LED, and a large, common electrode on the top.

An increasing number of industry players however are developing structures where RGB emitters are pre-assembled on a package with redistribution layers. Those packaged microLED are often referred to as "chiplets" or "MicroLED in Package (MIP)". The concept is similar to the "Integrated Micro Devices (IMD)" or "N-in-One" packages found in miniLED direct view displays [3]. Figure 6 shows the author's proposed classification of the different types of MIP that have been proposed so far.



| Type I | | Type II MIP | Type III | Type IV |
|---|---|---|---|---|
| RGB emitters only (with RDL on interposers) | | RGB emitters + microdriver IC on same plane | Stacked RGB emitters + micro-driver IC | |
| Lateral arrangement | Vertical arrangement | | Native RGB (Image: X Display) | Blue + Color Conversion |
| Mass transfer of RGB emitters on an interposer. Dicing | Stacked epiwafer + through via interconnects | Mass transfer of RGB emitters plus micro-driver ICs on interposer. Dicing | Mass transfer of RGB emitters onto a driver IC substrate (CMOS or TFT) | Bonding of single-color emitter wafer onto micro-driver IC wafer |
| 3x mass transfer step (red, green, blue) | Wafer-level manufacturing → no mass transfer | 4x mass transfer steps (red, green, blue, micro-drivers | 3x mass transfer | No mass transfer: Hybridization of LED wafer + color converter deposition and patterning |



**Fig. 6 overview of MIP architectures (top) and example of a Type I MIP from X-Display [4] (bottom)**

### 3.2 Manufacturing

Typical MIP manufacturing processes involve the mass transfer of microLED and, for "smart pixels". of micro-driver ICs onto an interposer substrate (typically, a silicon wafer), followed by singulation (dicing) of the individual MIPs.

In the case of type I, vertical arrangement, the assembly however is performed at the wafer-level, with wafers for each color bonded on top of each other and the realization of complex interconnects so each color can be controlled individually. Similarly, in Type IV architectures, a blue microLED epiwafer is hybridized onto a CMOS backplane before a green and red patterned color conversion layer is deposited and individual chiplets are cingulated.

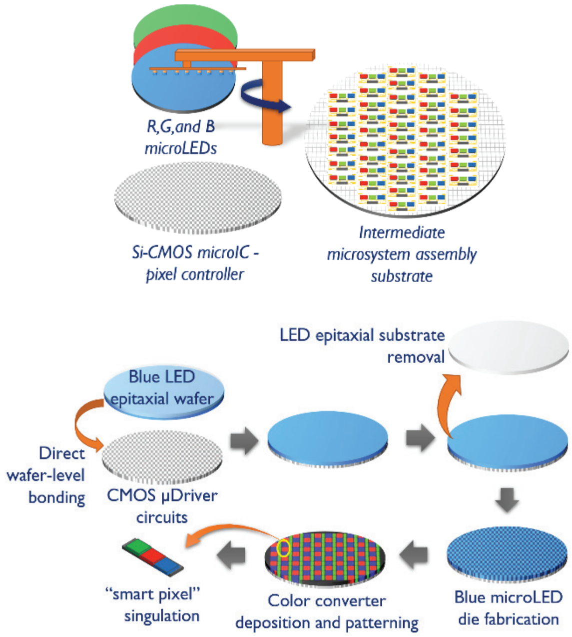



**Fig. 7 examples of manufacturing process flows for type II (top) and type IV (bottom) MIPs**

### 3.3 Potential benefits

From the perspective of the display manufacturer, MIPs could greatly simplify the assembly of microLED displays. First of all, MIPs reduce the number of transfer steps since a single transfer is required for the 3 colors. In addition, electrical redistribution layers in the MIP reduce the number of contacts (common cathode or anode, etc.) and allow for larger bonding pads with larger gaps on the display substrate, facilitating both the backplane manufacturing and the bonding process [5].

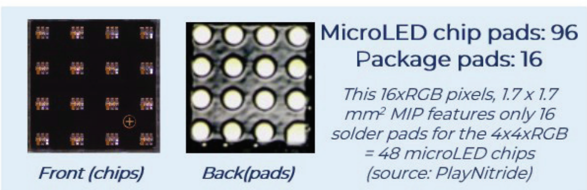



**Fig. 8 reduction on the number and size increase of bonding pads with MIPs. Courtesy of PlayNitride**

In term of yield management, testing and binning is greatly simplified by enabling functional (electrical) testing of the full MIP, i.e., the testing of individual microLED chips is replaced by the testing of a full, packaged component with large test pads. Similarly, repair is simplified as manipulating a package is easier than dealing with individual microLED chips which can be as small as 3 μm in size.

### 3.4 Discussion and challenges

The mass transfer and assembly of individual microLED chips with very small bonding pads is still required and quite complex. The only difference is that this complexity is now in the hand of the MIP makers rather than the display makers'. The MIP substrate can be complex, featuring multiple levels of electrical interconnections for the redistribution layers in order to reduce the number of bonding pads. This ultimately could add cost compared to directly bonding the individual microLED die onto the display backplane.

## 4 CONCLUSIONS

The jury is still out in term of total cost of ownership. In essence, MIPs transfer some of the complexity away from the display makers, toward upstream players (LED makers, packager). The process adds overall complexity but could provide significant benefits in term of yield management and lowers barrier of entry for new display makers which could purchase pre-assembled, tested pixels,Smart pixel (including microdrivers) or the use of separate microdrivers could also eliminate the need for TFT backplane, replacing those by simpler Glass Circuit Board with lower barrier of entry.

MIPs allow chip makers to extend their reach into the supply chain and capture more added value than if they were supplying microLED chip on carriers. This allows a better distribution of the capital expenditures required to enable a microLED supply chain.

How successful MIPs will be remains to be seen. MIPs are not "one-size-fit-all solutions". We anticipate that adoption will be dependent on the type of displays (e.g. large displays such as TVs) as well as on the individual preferences of the display makers.

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