MicroLED Displays: Industry Status and Roadmap

As pilot and production processes mature and improve, microLEDs could start competing with OLED displays in many application areas.

by **Ron Mertens**

MICROLED DISPLAY TECHNOLOGY OFFERS MULTIPLE advantages over conventional LED and OLED displays. This technology has been under intensive research and development for the past 10 years. Often it is seen as a natural replacement to LED and OLED displays, boasting the same excellent image quality, basic design, and flexible nature while also adding advantages (e.g., increased luminance, lifetime, and efficiency).

MicroLED displays are made of tiny, individual LEDs that are much smaller than conventional LED displays, typically less than 50 micrometers in size. They are self-emitting, allowing precise control over luminance and color. MicroLEDs have an inorganic LED basis, unlike the organic one used in OLEDs.

At Display Week 2024, Innolux demonstrated a 106-inch active matrix (AM)-microLED display built from 96 12.3-inch modules (**Fig. 1a**). The display uses 20 × 40 µm blue microLED chips with quantum-dot color conversion and a low-temperature polycrystalline silicone (LTPS) backplane. They also showed a 12.3-inch AM-microLED display with an LTPS backplane in monochrome blue (**Fig. 1b**).

MicroLEDs have notable advantages over OLEDs:

- increased luminance and efficiency;
- increased durability (temperature range);
- increased lifetime;
- decoupled production processes; and
- the ability to create extremely high aperture displays to enable higher transparency displays and an increased ability to embed behind-the-display sensors.

However, despite these advantages and the fact that microLEDs rely on an established and mature LED industry, it seems that even after 10 years of research, challenges must be overcome before mass production of microLED displays can occur. These include developing

- a high-quality, reliable, and low-cost epiwafer production process;
- a high-efficiency and manageable full-color architecture and process;
- a reliable, fast, and low-cost mass transfer process; and
- high throughput inspection and repair processes.

Early Developments and Considerations

The microLED industry is still in its nascency, with minimal market penetration into the display industry. Although dozens of technology developers cumulatively are investing billions in microLED research and development, the technology is not able to compete yet in the main display industry markets (wearables, smartphones, IT displays, and TVs).

Cost is one challenge hindering widespread adoption. When considering the cost of a microLED display, microLED chips represent one of the largest (if not the largest) cost factors.

Reducing the cost of LEDs is a three-pronged approach, as microLED developers likely will need to improve all three aspects to achieve cost competitiveness with OLEDs. One is to use larger wafers to reduce the production cost per area (and therefore reduce the cost of individual LEDs). The second route is to produce smaller LEDs, which means that more LEDs can be extracted from the same wafer size (thus reducing the space between LEDs—the street size—also will result in more LEDs per wafer). Finally, it is vital to improve wafer use by reducing

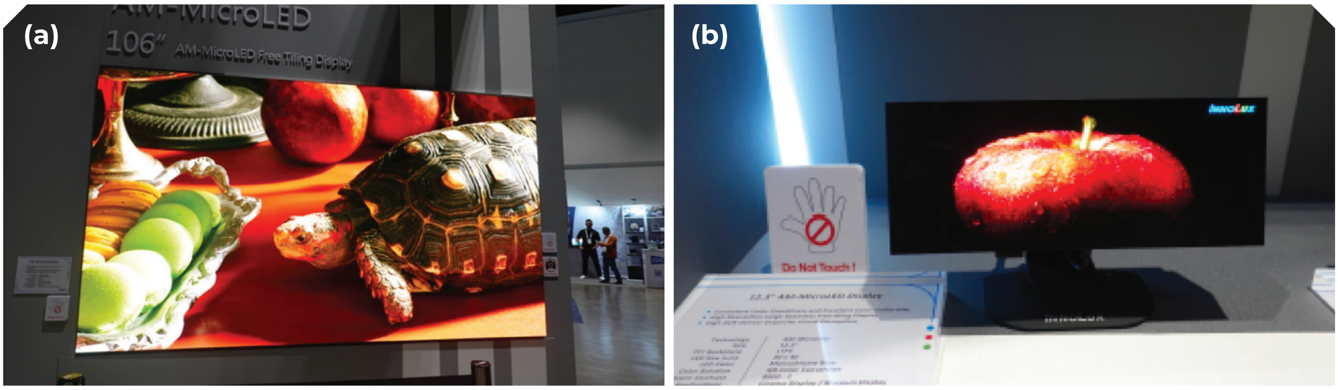

Fig. 1.

Innovations from Innolux at Display Week included (a) a 106-inch AM-microLED display and (b) a 12.3-inch AM-microLED display prototype.

defects and using a transfer process that can utilize more LEDs from the same wafer (i.e., the edges of the wafer).

Some companies also seek next-generation LED deposition processes, material platforms, and related technologies, which could lead to drastic improvements in the cost structure of microLEDs.

In early 2024, Apple withdrew from the microLED industry, or more accurately, it canceled one of its leading microLED projects that aimed to produce microLED wearable displays for a future Apple smartwatch product. Apple's withdrawal caused some pessimism among display professionals, as the US-based consumer electronics leader reportedly invested billions of dollars into this project and did not manage to achieve mass production.

However, this pessimism may be unfounded. While microLEDs are taking longer to progress than desired, the technology's future still looks promising.

Apple's expectations may have been overly optimistic, and their partners may not have been ready in time for the project's goals. It also aimed at a challenging first application—competing against excellent and low-cost active-matrix OLED (AMOLED) wearable displays, which is no small feat.

MicroLED displays slowly are entering the market (**Fig. 2**), albeit at a remarkably low volume production, for specific applications:

- tiled displays;
- augmented reality (AR);
- luxury smartwatch displays; and
- transparent displays.

With tiled displays, the ability to seamlessly (or almost seamlessly) tile together microLED modules and create large displays has opened a small market—ultra-premium large-area high-quality displays.

In 2016, Sony started selling such displays, and other companies, including Samsung, LG, Konka, and TCL, soon followed. It is possible to buy displays ranging from approximately 89 inches to pretty much any size you want. But costs are still high, starting at ~$100,000 for the smallest microLED TVs.

The market for such displays is quite limited, and only a handful of such displays are produced each year. The production processes used are still far from relevant for mass production of consumer TVs.

The AR market seems to be a perfect fit for microLED technology. As a start, waveguide-based optical engines require extremely bright displays, which cancels out OLED as a possible light engine. To create small, high-density, and high-quality complementary metal-oxide semiconductor (CMOS)-based microLED displays, someone could use a monolithic process, which means that LED arrays can be bonded from the source wafer to the CMOS backplane wafer without a transfer process. This is far from easy, but at least there is a clear path toward the production of high-luminance monochrome microLED microdisplays that can be used in commercial AR devices. In fact, JBD already has started to produce such panels commercially and has achieved several design wins with Vuzix, Xiaomi, TCL, Meizu, and others.

Current microLED displays on the market are quite basic—monochrome displays with low resolutions—but they are finding a niche, especially in China, in AR headsets. MicroLED microdisplay technologies are progressing quickly, with many companies involved in intensive research and development. One thing to keep in mind is that the AR market is still at an early development stage, and it is progressing hand in hand with microLED display technologies, which could be good timing for microLED developers (if AR takes off).

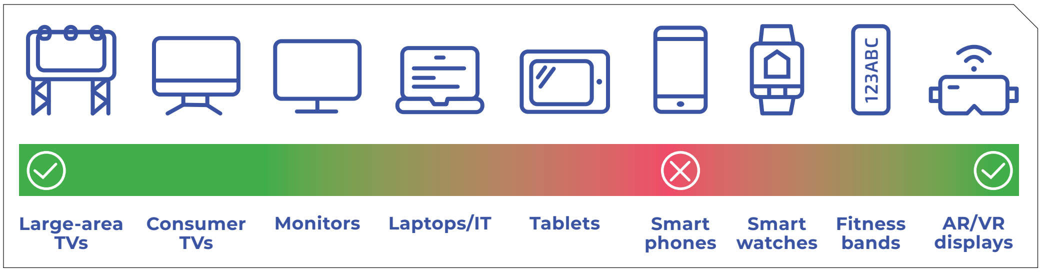

Fig. 2.

MicroLED adoption readiness in the display market.

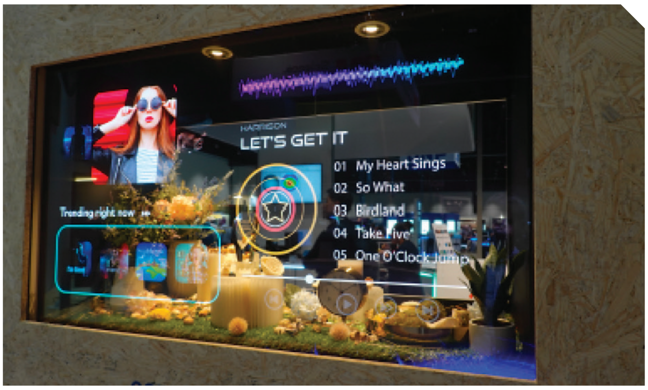

Fig. 3.

A 60-inch transparent microLED AUO prototype at Display Week 2024.

Wearable displays are a good fit for microLEDs; these are small displays with a limited number of pixels, with efficiency and luminance playing an important role. That was presumably the reasoning behind Apple's decision to develop and attempt to produce microLED wearable displays.

The main challenge, it seems, is that the competition is quite good: high-end wearable AMOLEDs offer high luminance (up to 3,000 nits), high image quality, and a relatively low price. Achieving such high quality and increased performance with microLED displays and at a comparable low cost is not yet realistic.

In early 2024, AUO started producing wearable microLED displays, and it is estimated that the first product (a luxury smartwatch) to adopt this display will be launched by the end of the year.[1] The display likely will cost a considerable premium compared to high-end AMOLEDs.

The high aperture ratio of microLED displays enables a much higher transparency compared to OLED displays (**Fig. 3**). Many companies are developing such displays and have demonstrated impressive prototypes and even initial production. The main problem in this segment is the lack of market demand.

One of the challenges of the microLED industry is that it has not yet settled on a production process, material platform, or architecture. In the OLED industry, all AMOLED fabrication plants (fabs) use the same basic technology to produce AMOLED displays. This makes it easy for equipment manufacturers and technology developers to focus and align their efforts and resources into one track. Of course, alternative processes and technologies exist in the OLED industry as well (e.g., ink-jet printing, organic vapor jet printing, and thermally activated delayed fluorescence emitters), but these efforts still are not applied in mass production.

When it comes to microLEDs, we see a proliferation of processes, technologies, and architectures compared to other early-stage display technologies. The main reason is that a "good enough" track has yet to be found to enable mass production. In addition, the challenges are so diverse that unique solutions likely are needed.

This industry landscape means that equipment and technology developers are faced with a difficult choice. They can choose to be prudent and wait on the sidelines, possibly making them late to the game if and when microLEDs take off. They also could gamble on a single technology or process and put all their efforts into one path. Another option is to split the effort into several tracks.

This situation is not ideal for microLEDs' long-term viability. However, there is another (less likely) scenario in which the microLED display industry would evolve in a different way than the LCD and OLED industries: with many different small-scale producers each choosing their own unique process and technologies. This can complicate things in many ways, but it also can afford unprecedented specificity and customizability that could enable market niches and needs.

"Recent market setbacks underscore the need of advancing next-generation technologies like microLEDs in prominent display segments such as wearables," said Vicente Calvo Alonso, CEO and co-founder of Comptek Solutions. "Despite their promising potential, mass production of microLEDs still faces significant hurdles, including low yields and high costs. Innovations that address these challenges will be crucial. Once achieved at scale and affordable prices, microLED displays are poised to surpass existing technologies like OLED, introducing a semiconductor-based value chain."

Making Inroads to the Future

To make the most of this technology and its potential, we need to consider the current state of affairs:

- MicroLED displays are not yet fully commercialized, but early production in niche areas has begun.
- Production processes still are only half-mature, which means that costs are high.
- There is not a clear path toward mass production; open questions regarding processes, material platforms, and architectures still exist.
- OLED displays pose as a tough competitor, offering high-quality displays at relatively low costs. OLEDs also are improving rapidly in terms of brightness and efficiency.
- As Apple cancelled its microLED project, the industry is in somewhat of a depressed state, which is especially evident from the side of investors who are hesitant to invest before the smoke clears.

Following a survey within the MicroLED Industry Association members, we have identified that in the near future (three to five years), the industry will likely focus on the following.

- Targeting niche applications in which microLEDs provide strong benefits demanded by the application or that current technologies do not provide a good enough solution for, or that it is possible to command a significant premium over current technologies (for example, ultra-large-tiled TVs, automotive displays, and luxury wearable displays).
- Attempting to develop new applications that take advantage of unique microLED properties (for example, the large aperture ratio that enables high-transparency displays, or the placement of sensors and cameras behind the display in an improved way).
- Adopting next-generation production technologies, processes, materials, and architectures that may pave the path toward

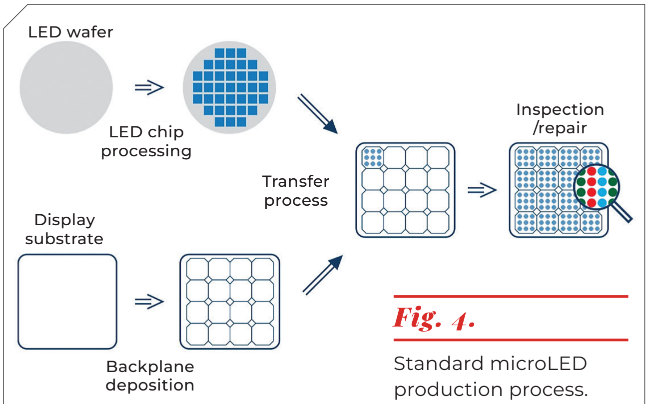

Fig. 4.
Standard microLED production process.

mass production. In first-generation microLED prototypes and displays, mostly first-generation technologies (e.g., a mechanical stamp-based transfer process) have been used. This was a good choice to produce prototypes and demonstrations and even small-scale production. But the industry realized that these technologies may not suffice when real mass production is required.

A reasonable time frame for most of these activities will take more than three years, which means that in the next three to five years, much of the focus will be on automotive displays, AR and virtual reality (VR), ultra-large-area tiled displays, and wearables. The mass market display industry applications (mainly TVs, smartphones, and IT displays) will simply have to wait.

"The market acceptance of microLED displays is based on the costs of the displays compared to other existing display technologies," said Oliver Haupt, director of strategic marketing at Coherent. "The sizes of microLEDs have come down to a single-digit micron level to reduce the material costs. Coherent has already demonstrated a laser mass transfer solution that is capable of handling microLEDs down to 5 µm with a high throughput.

"We do see continued interest in all our laser-based solutions and see good progress on the customers' side as well. Some are preparing for the first volume production, which will take at least a year from now."

An interesting thing about the microLED industry is that a production process can be decoupled, as there are two tracks performed on different substrates—the epiwafer growth and the main display substrate (**Fig. 4**). Unlike with OLEDs and LCDs, these can be performed in different locations or companies. This ability has some interesting implications for the industry, and this is definitely a trend to watch, even in the near future.

Some small-scale microLED developers have set their sights on the small-scale production of microLED displays: STRATACACHE in the United States and VueReal in Canada, among others. These companies are trying to take advantage of unique microLED production processes to create customized and unique displays and target markets that can be difficult to reach with standard OLED processes and fabs.

"As we continue to pioneer the advancement of smart contact lenses, we are excited about the transformative potential of microLED technology in shaping the future of wearable optoelectronic devices," said Valentyn Volkov, co-founder of Xpanceo. "The integration of cutting-edge microLEDs holds immense promise for enhancing the functionality and user experience of smart contact lenses, propelling us toward a new era of seamless and immersive visual interactions."

In fact, microLEDs also could take part in applications beyond the display industry. A good example is matrix-type automotive lighting, and another is optical communication.

"We believe that microLED technology, depending on application context, may have very interesting specs for optical communications for short (5 to 10 meter, or even shorter) distances, rack to rack, or chip-to-chip communication (e.g., HPC [high-performance computing] or AI [artificial intelligence] applications)," said François Templier, program manager of displays and display systems at CEA Leti. "We are especially working on the microLED part, a lot of synergies with our display development. While we are performing advanced R&D, it is very difficult to tell when the technology will be market ready; it may take some time to develop relevant technological bricks, as there is not only a microLED part."

Looking beyond 2030, things look bright for microLED displays. In terms of performance, the advances of microLEDs could far outpace OLEDS' advances. In fact, many technologies used to enhance OLEDs, such as microlens arrays or LTPO, can be applied to microLEDs as well. This would create an increased performance gap for microLEDs. It is also likely that the industry will continue to demand high-efficiency displays, as environmental issues and new mobile devices take center stage.

"The last decade of progress in microLED displays has been focused on 'can we make it work?' As the product rollouts at Display Week 2024 clearly demonstrated, the answer today is 'Yes, we can,'" said Wayne Rickard, CEO of Terecircuits. "Now the industry is making progress on the next prerequisite for mass adoption, which is 'can we make these displays profitably, at commercial-scale volumes?' We have every reason to believe the answer to that question is also a resounding yes, as the next decade will show.

"For our part, we are focused on high-yield, high-throughput transfer of microLEDs smaller than 10 µm, too small to be handled by conventional placement tools, and even most of today's contenders for mass transfer."

By 2030, it is likely that the cost of production for microLED displays will drop dramatically, as pilot and low-level production processes mature and improve. By that time, microLEDs could start competing with OLED displays in many application areas. ID

Reference

[1] Mertens, R. (2024). AUO stays committed to microLED technologies, plans to increase investments. *MicroLED-info*. https://www.microled-info.com/auo-stays-committed-microled-technologies-plans-increase-investments

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