MicroLED Association

White paper:

MicroLED Smartwatch Displays in 2023, LED Cost Analysis

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By the MicroLED Industry Association

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Progress in MicroLED technology and industry brings about increasing estimations that a leading consumer electronics producer will put a microLED smartwatch display on the market in 2023 (1).

This analysis document will go over the technologies and cost measures required to reach this goal - an actual mass-produced microLED display, with a focus on the cost of LED chip production.

The analysis will start with a comparison of MicroLED vs. OLED displays, to understand why makers would choose to adopt a microLED display.

It will go on to present two different analysis approaches, bottom-up and top-down. At first, we estimate the price target of a next-generation wearable display and the premium the market would receive over current technologies. From the complete display price target, it is possible to extract the price target of the LEDs themselves which is used to estimate the microLED chip size required to achieve that target (drawn from a specific wafer size and technology), examining whether this is technologically feasible today.

Our top-down analysis starts with the state-of-the-art microLED production capabilities, which is then used to calculate the likely chip size and resulting production costs for entire displays.

Both analysis methods end up with similar numbers and conclusions, which gives us more confidence in our conclusion. This analysis and its conclusions complete our LED cost analysis for a 2023 microLED smartwatch display.

MicroLED vs. existing OLED displays

There are two main reasons for adopting a microLED display over existing OLED displays: increased efficiency and brightness. Looking at the latest OLED displays, for example the one used by Apple in the Watch Series 8, these displays offer excellent performance - with a brightness of 1,000 nits, high pixel density, and a highly-efficient LTPO (2) backplane. It seems highly unlikely that a microLED display will offer a noticeable boost in display quality. The OLED display is quite efficient, but increasing the efficiency further will prolong battery life (or enable the adoption of a smaller and lighter battery).

Apple Watch device

Taking all this into account, it appears that the microLED display, beyond a marketing advantage, will not be able to provide a real revolution in display quality or efficiency - but it could be an excellent step forward. This means that the price premium that device makers will be willing to accept will not be substantial.

MicroLED display cost targets

It is estimated that the 1.78" AMOLED display used in the Apple watch, which is probably the most advanced OLED on the market, costs around $20 (3). We estimate that the target price of a similar microLED display should exceed $40.

The leading cost factors for microLED display fabrication are:

- Backplane production
- LED chips fabrication
- Depreciation of equipment: transfer, inspection & repair, etc.
- Takt Time related costs (4)
- Other costs such as labor, controller, materials and more.

It is out of the scope of this document to discuss most of these costs - we will focus on the LED costs, which is one of the major cost drivers. To reach our goal of $40 for the whole display, we will set a target of $10 for the LED chips.

Bottom-up Analysis: Price Targets for MicroLED Displays

MicroLED LED size targets

A display quality on par with Apple's Watch Series 8, will require a resolution of 448x368. This translates into 494,592 different LED chips (5). This means that each microLED chip will cost $0.00004043 USD.

We estimate that the first microLED chips will be produced on 150 mm wafers (6). A typically-used number for the production of a 6-inch wafer with a blue LED (7) epiwafer LED stack, complete with chip processing, is about $2,500 USD.

Combining the target LED cost and the wafer cost, we end up having to create 61.8 million LEDs from a single wafer, with a usable area of around 16,000 mm2 (8). If we add epiwafer LED yields to our calculation, we get around 68 million LEDs (9). This means that the area of each chip (plus the spacing) is about 0.0002353 mm2 or 235.3 um2. We finally arrive at the target microLED size - about 10 um (10).

A 10x10 um chip size is certainly an attainable chip size in today's technology, although this will require very fine chip handling and other related technologies (for example, the ability to deposit a phosphor color conversion layer on such small chips is not straightforward, which may limit the color conversion technology of choice to quantum dots).

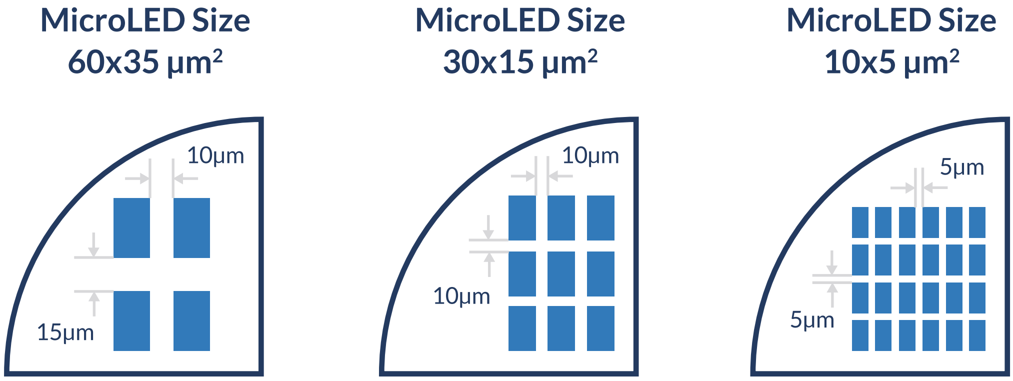
MicroLED wearable display – cost target

Following our rough calculations, we realize that if a microLED display is produced from 10x10 um microLED chips, on a 6-inch wafer, it is quite possible to achieve a target cost of about $10 for the LED chips.

Top-Down Analysis: MicroLED Production Status

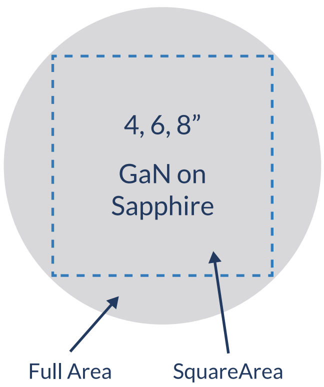
The top-down analysis is a simpler one. We are estimating the use of 6-inch wafers, which include a full-area of 18,241 mm². We have used three scenarios for chip sizes:

- 60x35 um, with spacing of 10x15 um
- 30x15 um, with spacing of 10x10 um
- 10x5 um, with spacing of 5x5 um



In current technology, the last scenario is quite feasible, and is the one we base our calculations on as these smallest LEDs will enable low-cost displays.

While a complete wafer will enable around 120 million 10x5 um chips to be produced, it is not reasonable to assume that the entire wafer area will be usable. Assuming that only a square area will be used, we estimate a 100x100 mm usable area, which means that one can produce 66.6 million 10x5 um chips on such a wafer.



		60x35 µm²	30x15 µm²	10x5 µm²
4”	70x70 / 4900 mm²	1.452M	4.9M	32.6M
	Full Area / 8107 mm²	2.4M	8.1M	54M
6”	100x100 / 10000 mm²	2.96M	10M	66.6M
	Full Area / 18241 mm²	5.4M	18.2M	121.6M
8”	140x140 / 19600 mm²	5.8M	19.6M	130.6M
	Full Area / 32430 mm²	9.6M	32.4M	216.2M

Calculation of wafer area and usable LED chips available

If we go back to our cost calculation, this results in a similar number of chips-per-wafer, which will enable a good enough LED cost of production (albeit with a different chip size).

Conclusion

While our calculations show a positive outcome, it is important to realize that there are still many challenges before actual mass production can be reached:

* Epiwafer deposition and chip processing yield and stability
* Quality control
* Full-color architecture
* Transfer process quality and efficiency
* And more...

It remains to be seen whether such a microLED wearable display will indeed be introduced in 2023 and 2024. The display industry has a long history of unfulfilled expectations - but there's no limit to innovation and the drive towards higher quality displays and we are sure that in the near future we will see the successful production and adoption of microLED displays across many applications.

Further Discussion Points

Color conversion or RGB? what are the implications?

The realization of a full color microLED display requires a choice between two architectures:

* Full color RGB microLED architecture, which uses native LED chips of three colors (red, green and blue).
* An all-blue microLED architecture, that uses color down conversion to emit red and green colors.

Each use case has its advantages and disadvantages, and the choice of color architecture effects several aspects of the production process (transfer process, epiwafer growth, and more). Here are a couple of things to consider:

* A full color RGB microLED must rely on native red emitters. Most red emitters are made from a different material class than blue and green emitters, as GaN red emitters are ineffective. This complicates the backplane of the display. There is much progress lately towards efficient red emission, or the adoption of 3D nanowire structures that can emit all colors from the same material platform.
* An all-blue architecture requires color conversion, which could be a difficult task as microLED sizes decrease. In addition, the color conversion reduces the efficiency of the display.

Why direct bonding is not an option for wearable displays

As the transfer process (which was out of scope for this document) is still a major challenge in microLED production, there is a lot of discussion on direct-bonding, or a monolithic design. The idea is that the LEDs are transferred from the epiwafer to the display backline in a single step, wafer to wafer (11).

Such a transfer-free process is attractive, but it has its drawbacks. First of all, it limits the final display in size (even at 300 mm, the maximum display is small), it forces the adoption of a highly expensive silicon wafer backplane, and it eliminates the possibility of LED distancing. The LEDs on the epiwafer are grown close to each other, much closer than is required in most displays. This is why direct-bonding, or a monolithic design, is only suitable for AR/VR displays - where the near-eye operation makes the high density a good idea. In addition, this is a premium market that can tolerate the higher costs.

For wearable displays, this architecture and process could theoretically be possible - but in reality, it will incur high costs. If we return to our calculations, on a $2,500 150 mm wafer, we can insert something like 5 wearable-sized displays. This means that the cost of each display is too high (and remember that this is just the cost of the LEDs).

Footnotes:
(1) You will see the company name mentions in media reports, but microLED technologies are being developed by many display makers and leading consumer electronics companies.

(2) An LTPO (or low-temperature polycrystalline oxide) is a relatively new backplane architecture that actually combines two TFT technologies, LTPS and IGZO (Oxide-TFT) that together enable variable refresh rates, a feature used in high-end devices today to conserve power in applications that do not need fast motion support.

(3) In 2021, for example, Counterpoint Research estimated that the Watch Series 7 OLED display costs $17.68.

(4) One of the main challenges in microLED production, is the process of transferring the LED chips from the epiwafer to the final display substrate. Not only is that a complicated and lengthy process, we also have to take into account the fact that the LED yields and the transfer yields are not 100%, which means that the LEDs have to be inspected - and repaired - which can pose a challenge. At a 99.99% yield, a typical smartwatch display will suffer from around 50 damaged LEDs, which will have to be fixed. At a 1 min per LED inspection and repair process, it will take almost an hour of work for a single display. This means that the transfer process will have to be very efficient and with high yields to make sure production efficiencies are maintained. Another possibility is to introduce LED redundancy, but this increases the costs of production and backplane complexity quite dramatically.

(5) We assume 3 sub pixels per pixel. As was mentioned in footnote #4, the use of redundancy may increase the LED chip count.

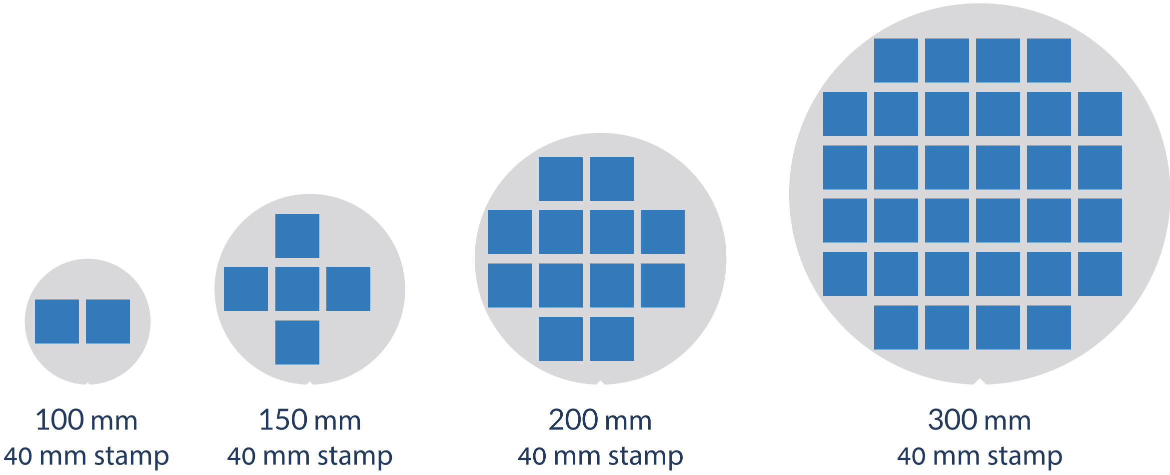
(6) High-end LED production is currently performed at 150 mm (6”) wafers. MicroLED display applications will require high LED quality and extreme cost measures, as we discuss in this white paper, so there is a strong push into adopting larger substrates - 200 mm or even 300 mm (12”) wafers. This will certainly help in decreasing the price per LED, but it also increases production complexity and most equipment makers are not ready to support these larger wafer sizes.

(7) The cost of a native red LED wafer is higher than that, today. Adopting a blue LED and color conversion architecture

may mean that there's no need for any red LEDs.

(8) A perfect round 150 mm wafer has an area of 17,671 mm2. But actual wafers are not 100% round, and the edge of the wafer is not usable. We estimate that about 10% of the wafer area is not usable.

Note that we do not take into account the wasted LEDs due to stamp size. Most transfer processes are based on stamping, and there's a trend of increasing stamp size so that the transfer process is faster and more efficient. However, a larger stamp also results in wasted wafer area, as can be seen in the image below.



Wasted wafer area for a 40 mm stamp (source: ALLOS Semiconductor)

Note that the wasted area decreases as the wafer growth. A 40 mm stamp sounds like a very big stamp as it is almost the same size of the final wearable display - but to create an economic process, large substrates will have to be produced and then cut into individual displays (following the transfer process). As we said, the larger the stamp, the more efficient this process is.

(9) We estimate that the LED yield is 90%. This includes completely defective LEDs, but also LEDs that have too large a deviation in efficiency or light color input. The requirement for a high-end display are quite high.

(10) We assume a spacing of about 5 um between LED chips, which is something that the industry is certainly capable of today. This means that if our target chip is about 15x15 um, we need to reduce about 5 um from both dimensions.

(11) Another option would be to grow the LEDs directly on the backplane wafer, which is a method that some companies are considering and developing.