Merits and Challenges of MicroLED Technology

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Abstract

This paper presents a techno-economic analysis of MicroLEDs for mobile display applications. Based on this analysis, a technology goal post is proposed to address a large portion of the $120B display market with GaN-based MicroLEDs. It is shown that the cost structure of mobile displays favors 300mm silicon wafers and nanostructures (e.g., nanowires) that can enable monolithic red, green, and blue emitters, and truly massive transfer. This vision comes with several technical and ecosystem challenges and requires large investments in several aspects of the ecosystem.

INTRODUCTION

The revenue of emissive OLED displays used in mobile devices (e.g., smartphones, laptops, smartwatches) exceeded $40B in 2020 by some estimates. In 2026 it is projected by some analysts that mobile displays will represent ~75% of the total display market (cf. Fig. 1 and Fig. 2). The dominant mobile display technology has to offer the lowest figure of merit (FOM = $/(lm/W)). To reduce this FOM we must increase the emitters power efficiency (lm/W) and reduce the cost of production. Innovation can break the cost-performance tradeoff tyranny. But innovation requires up-front R&D investment. GaN MicroLEDs, which have been explored for emissive mobile displays for two decades now [1], promise doubling of lm/W [2,3]. Challenges remain for the cost of production of these displays. Solving these challenges may require more than what have been reported for industry-wide investments in this technology [4]. This amount does not compare well with other technologies that are just as complex as MicroLED displays (cf. Fig. 3).

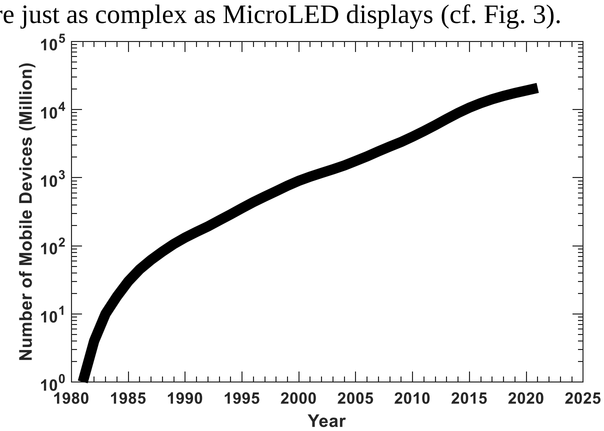

Figure 1. Cumulative number of mobile devices (smartphones and PCs) shipped versus time.

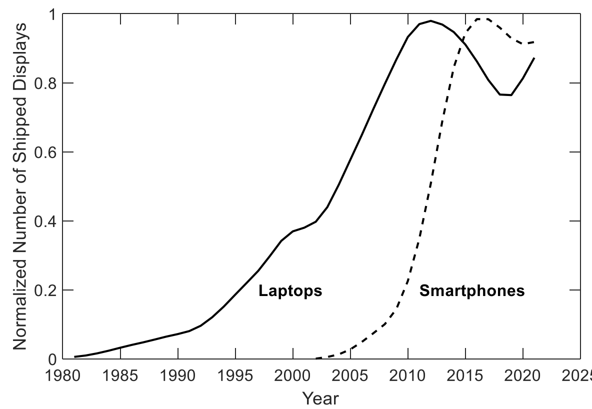

Figure 2. Normalized (to maximum) shipped mobile displays in smartphones and laptops versus time. Are there new devices that will ramp in the future?

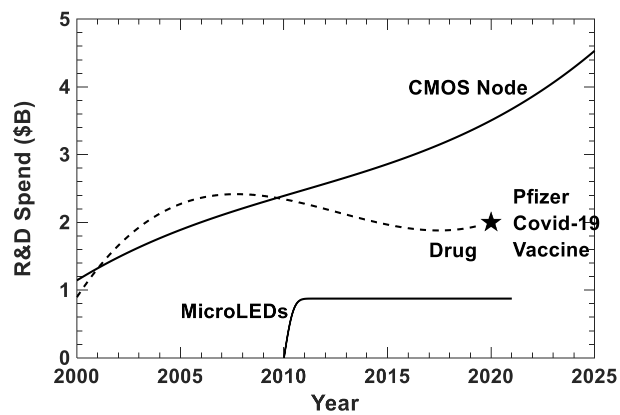

Figure 3. R&D spend per year on various significant technologies (drug [5] and CMOS technology [6]) and the MicroLED technology [4]. The MicroLED spend is averaged over 8 years (data for each year is not readily available).

In this paper we discuss the challenges with MicroLED manufacturing, i.e., transfer technology and large MicroLED wafers for breaking the cost barrier and to enter the market. We present a techno-economic analysis of MicroLEDs for mobile display applications. Based on this analysis, a technology goal post is proposed to address a large portion of the $120B display market with GaN-based MicroLEDs.

POWER EFFICIENCY GAP

In laptop displays, the display consumes ~75% of the total system power. This presents a major challenge for battery lifetime. Smartphone device also face a battery gap problem as shown in Fig. 4.

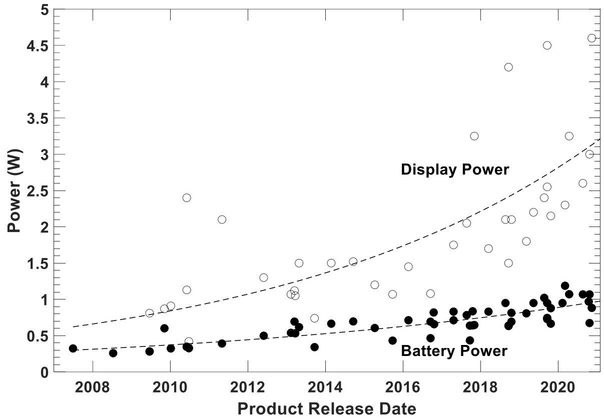

Figure 4. Power consumed by display of several commercial smartphone devices and battery power capacity versus time of product introduction. A battery gap exists and presents a user experience challenge.

The display power efficiency depends on the use condition for each device. For example, laptop applications use largely white backgrounds, which means that the emitter power in the case of emissive displays dominate power consumption. On the other hand, smartphones rely less on white background and the lm/W metric is influenced more equally between the emitter power and display electronics power. High emitter power efficiency is therefore very important to overall display power consumption, especially for outdoor use when the required luminance is high. Currently, mobile displays made of OLEDs have power efficiency of ~13 lm/W under all-white condition [2], as shown in Fig. 5. It is observed that lm/W saturated over the past 7 years. Displays made of GaN MicroLEDs promise ~25lm/W under all-white condition. The promised higher efficiency relies on fundamental differences in materials used. As such, it is argued that OLEDs' power efficiency and luminance cannot be simply optimized to reach parity with MicroLEDs' promised lm/W.

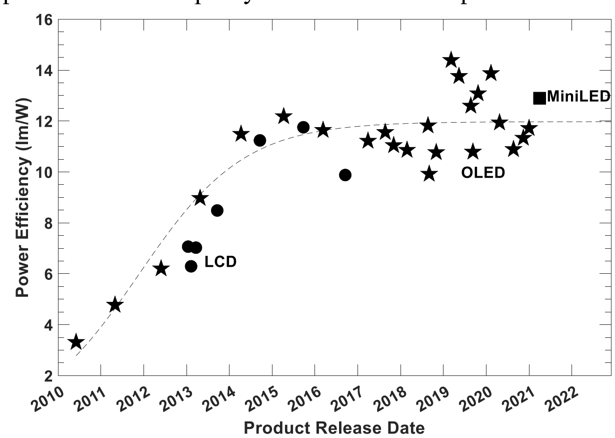

Figure 5. Historical power efficiency of smartphones and laptops with LCDs, OLEDs, and MiniLEDs. The dotted line is guide to the eye. Raw data for power were obtained from www.displaymate.com and analyzed using the methodology published in [2]. The displays had all-white images.

Power efficiency envelope curves for OLEDs and MicroLEDs are shown in Fig. 6. GaN MicroLEDs are superior to OLEDs for blue and green colors, but inferior to OLED for red color. The GaN LED efficiency is much less than 6%, which was found to be the minimum required efficiency to achieve sizable improvement of lm/W metric [3]. Improvements in red GaN efficiency may be accomplished by low temperature InGaN epitaxy [7]. MicroLEDs are also superior to OLEDs in drive current capability, as shown in Fig. 7. The root cause of the superior drive current is their higher electron and hole mobility, and the superior device structure [8].

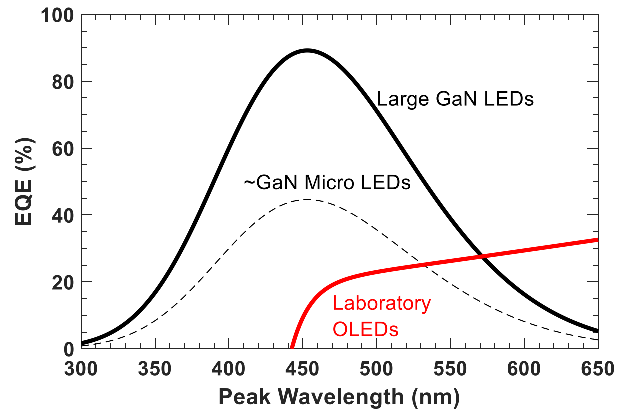

Figure 6. Envelope curves for external quantum efficiency (EQE) versus wavelength for OLEDs and GaN MicroLEDs. Data used to construct the envelope curves are shown in [2].

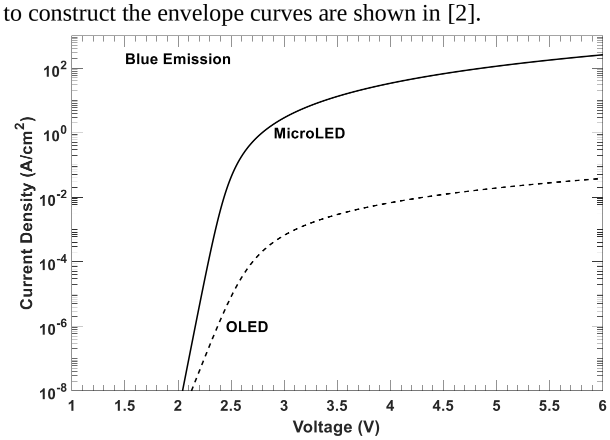

Figure 7. I-V curves for blue OLED and MicroLED. The calculations are based on physics-based models [8]. MicroLEDs have much higher "drive current" compared to OLEDs.

PRODUCTION COST GAP

The other factor in the FOM discussed above is the cost of production. Here, OLEDs have an advantage over MicroLEDs, assuming same production line yield, since OLEDs are manufactured on the display glass substrate itself, which can be as large as Gen 6 for mobile displays [9]. MicroLEDs on the other hand rely on using more costly semiconductor processing to fabricate the MicroLEDs on small wafers (e.g., diameter ≤ 12"). Moreover, new device transfer technologies (both equipment and process) have to be developed to move millions of MicroLEDs from their native substrate to the glass display substrate. This process can be really expensive especially for smartphones (diagonal ~6”) and laptops (diagonal ~14”). Example transfer methods are shown in Figures 8-10. The pick & place methods shown in Fig. 8 rely on small stamp and large wafer utilization. The direct transfer method (DTM) shown in Fig. 9 and Fig. 10 rely on transferring the MicroLEDs directly from wafer to glass backplane and less wafer utilization. The balance between wafer utilization and the throughput of the transfer method will determine the optimal cost point. Example cost calculations are shown in Fig. 11 and Fig. 12 for a 14” diagonal display. In Fig. 11 the display cost is shown using DTM with 12” and 8” MicroLED wafer size. Clear advantage is seen for the 12” case. In Fig. 12 the production cost is shown for two extreme cases: (1) Pick & Place with 6” wafers, and (2) DTM with 12” wafers and monolithic RGB emitters. The latter scenario results in cost parity with OLED displays of the same size. The results of Figures 11 and 12 indicate that reaching cost parity with OLED displays requires (1) 12” wafers, (2) truly massive transfer technology, (3) monolithic RGB. The cost of 12” sapphire wafer excludes sapphire from the option list as shown in Fig. 13. The truly massive technology works best for 12” wafers as demonstrated in Fig. 11. A monolithic RGB solution on 300mm silicon requires an innovative solution beyond planar LED structures to manage the lattice mismatch between GaN and silicon. Nanostructures have been proposed to enable monolithic RGB on 300mm silicon wafers [10]. But there are tradeoffs about selecting the optimal nanostructure to achieve monolithic RGB growth and high efficiency red and green LEDs. A possible stop-gap measure is to use high efficiency blue MicroLEDs on 300mm silicon wafers then use color conversion (e.g., quantum dots) for red and green emitters [11].

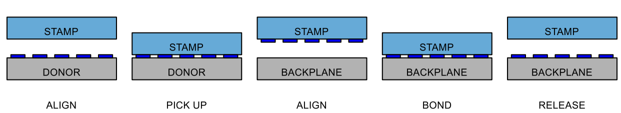

Figure 8. Transfer using a stamp (Pick & Place or PnP).

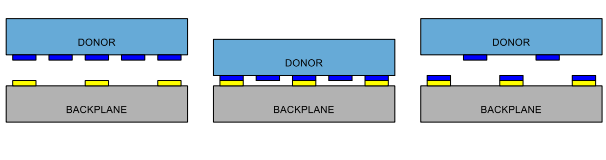

Figure 9. Direct transfer method (DTM) using selective bonding and selective releasing of MicroLEDs directly from their mother wafer [12]. The backplane is populated with copper protrusions that are designed to receive MicroLEDs with copper layer to produce a strong copper-to-copper bonding at high throughput. The laser from backside of the donor wafer is used to selectively de-bond (release) MicroLEDs that have been selectively bonded.

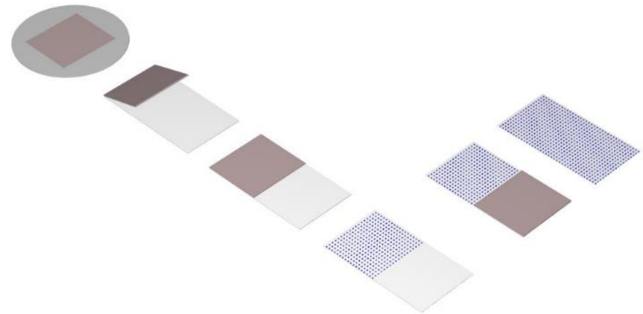

Figure 10. DTM of MicroLEDs from growth wafers directly onto backplane using large stamps [12]. A large stamp from a round wafer is used to stamp backplane, transferring MicroLEDs using the so-called “selective bonding” and “selective release”.

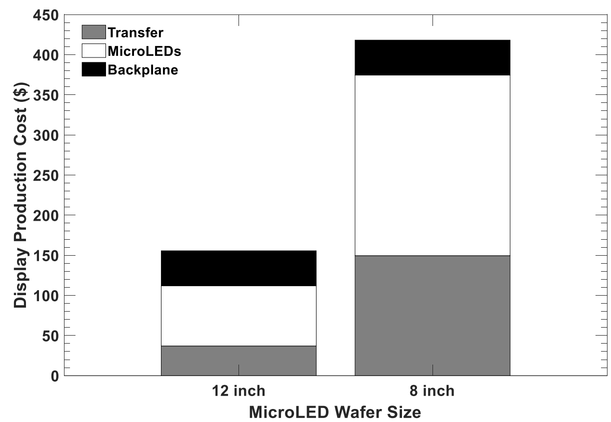

Figure 11. Estimated display production cost for 14” diagonal MicroLED display using “DTM” (a truly massive transfer technology) for 12” and 8” wafers. It is assumed that monolithic RGB is achievable and redundant MicroLEDs per color per pixel [13].

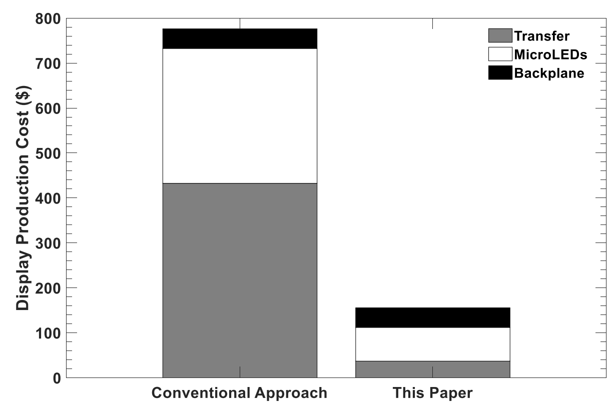

Figure 12. Estimated display production cost for 14” diagonal MicroLED display using current strategy (PnP + 6” wafers + one wafer per color) and proposed strategy (“DTM” + 12” wafer + one wafer per three colors).

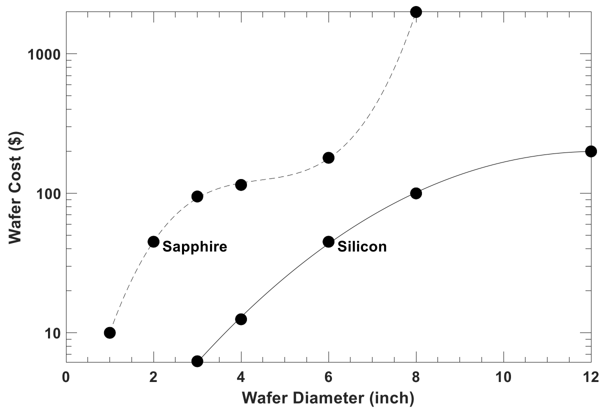

Figure 13. Commercial cost of wafers of sapphire and silicon versus wafer diameter. Silicon wafers are much cheaper than sapphire wafers at a given diameter.

Conclusions

A techno-economic analysis of MicroLEDs for mobile display applications has been presented. Based on this analysis, a technology goal post has been derived and proposed to address a large portion of the $120B display market with GaN-based MicroLEDs: mobile displays. It is shown that the cost structure of mobile displays favors 300mm silicon wafers and nanostructures (that can enable monolithic red, green, and blue emitters, and truly massive transfer). This vision comes with several technical and ecosystem challenges and requires large investments in several aspects of the ecosystem including the need for 300mm-wafer MOCVD reactor technology.

References

[1] H. X. Jiang, S. X. Jin, J. Li, J. Shakya, and J. Y. Lin, "III-Nitride Blue Microdisplays," *Applied Physics Letters*, vol. 78, no. 9, p. 1303, 2001.

[2] Khaled Ahmed, "Heuristics of OLED and Micro LED Efficiencies," , vol. 65, 2021, pp. 864-867.

[3] Khaled Ahmed, "Micro LEDs Efficiency Targets for Displays," in *SID*, 2019, pp. 125-128.

[4] SemiconductorToday, "Over $5B Spent on Micro-LED Development," *semiconductor-today.com*, vol. 16, p. 62, 2021.

[5] https://www.cbo.gov/publication/57126.

[6] https://semiengineering.com/big-trouble-at-3nm/.

[7] Khaled Ahmed, "High Performance Light Emitting Diode and Monolithic Multi-color Pixel," US Patent 10957818B2, March 23, 2021.

[8] Khaled Ahmed, *MicroLEDs: Physics and Technology*.: To Be Published, 2024.

[9] Eric Virey, Zine Bouhamri, and Claire Troadec, "MicroLED Display: Technology and Applications Status," in *CS Mantech*, 2022, pp. 105-108.

[10] Philippe Gilet and Ivan-Christophe Robin, "Nanostructures on Silicon to Solve the Active Display Paradigms," , vol. 49, 2018, pp. 684-687.

[11] Khaled Ahmed, "Design Heuristics of Color Conversion Films in Micro LED Displays," in *SID*, 2022, pp. 202-205.

[12] Khaled Ahmed, "Micro Light-Emitting Diode (LED) Elements and Display," US Patent 10923622B2, February 16, 2021.

[13] Khaled Ahmed, "Yield Statistics for Fault Tolerant Micro LED Displays," *SID*, vol. 51, no. 1, pp. 520-523, 2020.

Acronyms

GaN: gallium nitride
MicroLED: microscopic light-emitting diode
lm/W: lumens per Watt
OLED: organic light-emitting diode
MOCVD: metalorganic chemical vapor deposition
LCD: liquid-crystal display
R&D: research and development
DTM: direct transfer method
PnP: pick and place
FOM: figure of merit
W: Watt
lm: lumens
EQE: external quantum efficiency