Laser-Enabled Extremely-High Rate Technology for µLED Assembly

Val R. Marinov

Uniqarta, Inc., Fargo, ND, USA

www.uniqarta.com

Abstract

We developed a complete wafer-to-panel technology for extremely high rate assembly of µLEDs. The process involves transferring the µLEDs directly from the source epi-wafer to a quartz carrier from where they are selectively transferred to the panel using our Laser-Enabled Massively Parallel Transfer method with >100M units/hr.

Author Keywords

µLED assembly; massively-parallel transfer; µLED display.

1. Introduction

Micro-LEDs (µLEDs) are defined here as epi-layer, substrate-less LEDs with dimensions of <100 µm/side and a thickness of about 5-7 µm. µLEDs have come into the spotlight after Apple and Oculus acquired µLED startups. There are currently no µLED displays in mass production but the companies developing the technology believe that it has the potential to challenge OLED technology in the future [1]. Unlike OLEDs, µLEDs are typically based on III-nitride compound semiconductors which offer far higher total brightness than OLED products [2], as much as 30 times, as well as higher efficiency [3]. They also don't suffer from the shorter lifetimes of OLEDs. Another big benefit is their superior efficiency.

µLEDs are currently aimed at small, low-energy wearables such as AR/VR headsets and smart watches. Another market entry are large format display. The major reason µLED displays are not in mass production yet is the lack of commercially viable technology to place and interconnects the very large number of µLEDs required for these devices. This, according to many experts, is the major bottleneck that prevents the general production cost of µLED displays from going down [4].

Presented is Uniqarta's extremely high placement rate Massively Parallel Laser-Enabled Transfer (MPLET) technology for µLED placement that is applicable to a wide range of panels sizes. MPLET is a truly disruptive technology with a potential to revolutionize µLED and mini-LED display manufacturing.

2. State of the Art in µLED Assembly

The two major methods currently considered for assembling µLEDs in displays are wafer bonding and die bonding.

Wafer Bonding: The wafer bonding method is applied to create monolithic displays with integrated µLEDs on matrix-addressable substrates [e.g., 5]. In this approach, a standard LED wafer is etched to form µLEDs, which are then integrated with the transistor back plane. Advantages of this method include a very small pixel size and a mass transfer capacity. The drawbacks include the small overall size of the display, which is limited by the size of the µLED wafer, the need for the pitch of the donor array to match the pitch of the display, and the inability to exclude bad and subpar µLEDs from the transferred array.

Die Bonding: In the die bonding approach, discrete µLEDs are packaged on rigid or flexible substrates. One of the major advantages of the discrete approach is the capacity to create a large area display [6]. Die bonding methods fall into two categories, serial and parallel. In the *serial (sequential) method*, the µLEDs are placed one-by-one on the panel. This is an implementation of the conventional pick-place technology, which is not realistic when the number of assembled µLEDs is in the millions or tens of millions.

Most of the *parallel assembly methods* are based on the Micro Transfer Printing (µTP) pick-and-place technique [7], variants of which are under development by several companies. In essence, µTP uses a stamp to pick up an array of µLEDs and transfer it to a display substrate by "stamping" it. The advantage of this technique is that it allows for the placement of a large number of dies over a large panel size at a high rate. However, the µTP process requires a careful engineering of the stamp and the donor substrate. Using large stamps for high transfer rates may be problematic because of the pitch inconsistency resulting from manufacturing errors and the CTE mismatch between the stamp material (340 ppm/°C for PDMS), glass donor substrate (5-9 ppm/°C) and the panel material. An ambient temperature change of just 1°C will cause more than 30 µm mismatch between a 100 mm/side PDMS stamp and the µLEDs on a glass donor substrate. This would render such a stamp useless. Also, planned redundancy is required to mitigate the risks of dead pixels. Some solutions include placing two µLEDs at each subpixel [8], an approach that essentially doubles the material cost of the display and still doesn't guarantee the absence of dead subpixels. Another question is the compatibility of the µTP process with interconnection methods other than thin film lithography. Yet another issue is related to the need for redistributing the µLEDs at a pitch greater than the pitch of the source wafer onto a stamp-ready support substrate with adhesive tethers, from where they can be picked by the stamp, a step that complicates the production process and increases production cost.

Uniqarta's MPLET technology for extremely fast placement of µLED, described in the next section, is a comprehensive wafer-to-interconnected µLED assembly technique that addresses all the problems inherent to the µTP method.

3. MPLET Technology for Component Placement

MPLET's process flow is illustrated in Figure 1. The process starts with transferring µLEDs grown on the epitaxial wafer to a laser-transparent glass carrier which has a sacrificial layer (Dynamic Release Layer, DRL) spin-coated on its surface. This transfer is done using an intermediate transfer tape to ensure that the dies end up oriented on the DRL carrier active side away from the glass substrate, ready for flip-chip assembly. Conversely, the µLED can be transferred directly to the DRL carrier, in which case their active side will face the DRL and they will be placed on the receive substrate face up. In both cases the µLED are released from the source wafer using a laser liftoff (LLO) method. Once placed on the DRL, the µLEDs are ready for laser transfer, accomplished using Uniqarta's patented laser transfer process for high-rate assembly of ultra-small and/or ultra-thin semiconductor dies [9] modified for µLED placement and illustrated in Figure 2.

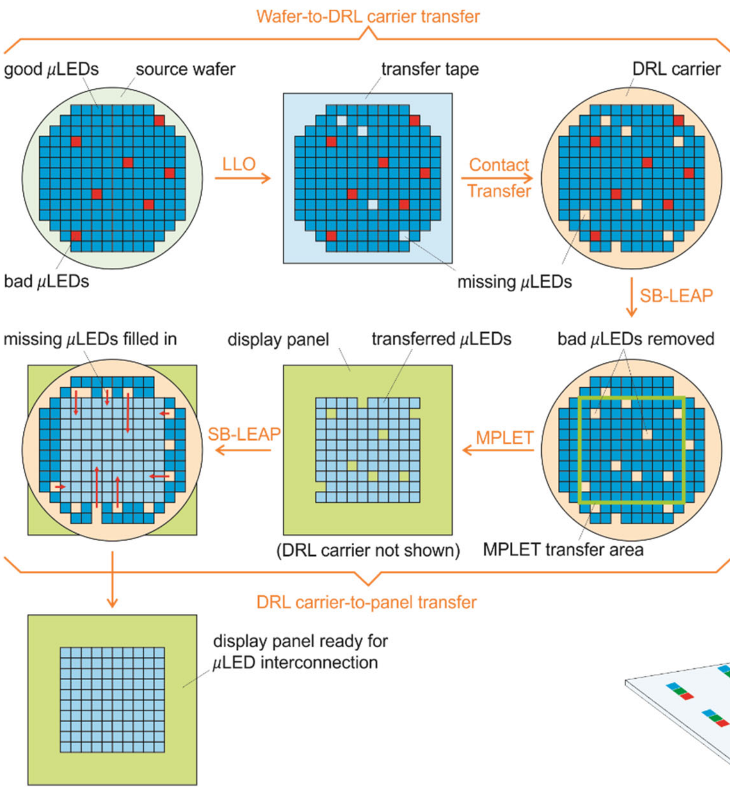

Figure 1. Process flow in Uniqarta's laser-enabled extremely-high rate technology for µLED assembly. SB-LEAP = single-beam laser transfer process; MPLET operates in a multi-beam mode, as explained in the text.

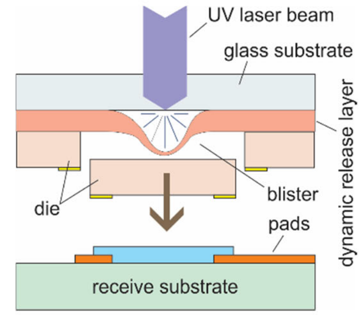

Figure 2. A schematic illustrating Uniqarta's laser transfer process.

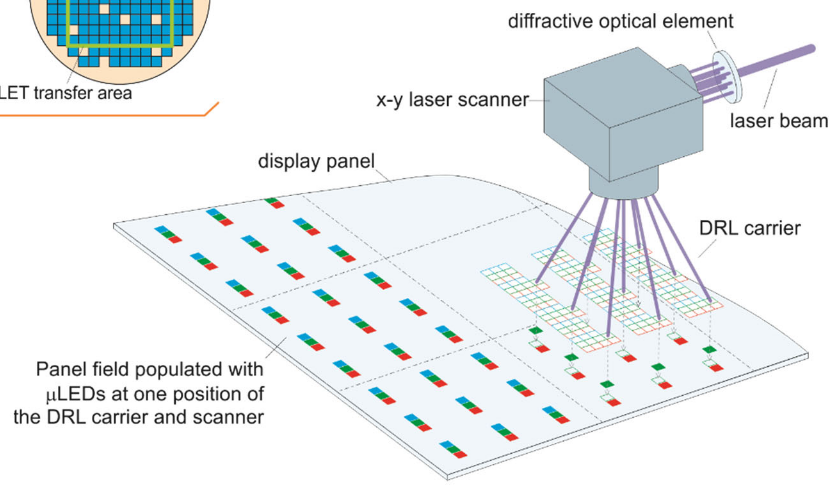

Figure 3. A schematic illustrating the MPLET concept. For simplicity, only a 3×3 beam array is shown although DOEs with much larger arrays are achievable. Note that all dies on the wafer could be of the same type – the colors in this figure are only used to indicate the subsequent die arrays transferred with one laser pulse.

In this process, the components to be transferred are bonded to the DRL. During laser transfer, a portion of the DRL is ablated by a short UV laser pulse through the carrier substrate to generate gases that create a blister in the DRL without rupturing it. The force exerted by the expanding blister, in addition to the gravitational force, initiates a transfer across a 10-300 µm gap onto a receive substrate where the die is interconnected to the rest of the circuitry. By scanning the laser beam across the many dies of a wafer, this process can achieve very high placement rates of 100K units/hr or higher. However, this single-beam transfer process is still not sufficient when a very large number of components need to be assembled for applications such as the µLED displays, chip-on-board LED lighting, IoT nodes, etc.

MPLET Technology: MPLET builds upon the single-beam laser-transfer process, extending its capability by transferring a large array of dies with a single laser pulse (the transfer process takes < 50µs). Instead of being scanned by a single beam, the wafer in MPLET is scanned via an x-y laser scanner with an array of "beamlets" diffracted from a single laser beam using a Diffractive Optical Element (DOE) (Figure 3). Each beamlet transfers one die, resulting in a placement rate equal to that of the single-beam process multiplied by the number of beamlets. The beam can be diffracted into tens of thousands of beamlets, limited only by the power of the laser.

Defect Management: A solution for managing defective µLED is an integral part of MPLET. Before laser transfer, the DRL carrier is processed by the MPLET equipment operating in a single-beam mode (the multi-beam to single-beam modification is simply done be removing the DOE from the optical train) and programmed using a wafer map to remove the bad µLEDs (Step 4 in Figure 1). Next, the panel is introduced and the system is operated in its multi-beam mode to rapidly place the remaining good µLEDs. Because of the previously removed bad dies, a certain number of incomplete die arrays will be transferred. This is dealt with in a final step in which MPLET is switched back to a single-beam mode and populates the empty subpixels using the orphaned µLEDs left on the wafer from the previous step.

A limiting factor in MPLET is the single-beam operation used in the defect management step, which becomes predominant at lower wafer yields, as seen in Figure 4. Another important conclusion is that MPLET doesn't necessarily require large beam arrays to achive extremely high placement rate. Smaller arrays will help with better utilizing the round source wafers while still providing placement rates in excess of 100M units/hr.

Technology Demonstration: Uniqarta has demonstrated key elements of the MPLET process. Figures 5a and 5b show the results from transferring µLED from the source epi-wafer to the

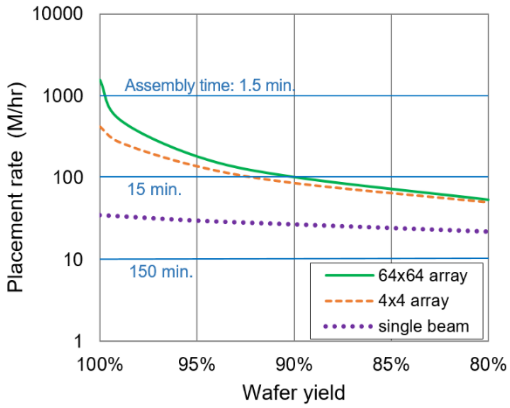

Figure 4. MPLET placement rate for different array sizes as a function of wafer yield. The assembly times are estimates for a 70-in, 4K display.

DRL carrier. The transfer was performed using the transfer method described above. We have also successfully demonstrated the single-beam laser transfer process's ability to place 55×32×6 µm µLEDs on the receive substrate with solder bonding pads (Figure 5c). Figure 5d is a frame capture of a video showing the parallel transfer of a 5×5 array of 42×42×6 µm dummy dies. Figure 5e shows the probing of 55×32×6 µm µLEDs soldered to a test substrate. We are in the process of bringing all these process components together with an objective demonstrating a demo µLED display later this year assembled with a placement rate of more than 10M units/hour.

4. Discussion and Conclusions

To become commercially viable, the large area µLED display technology must be able to compete effectively with the existing display technologies (OLED and LCD) and to make a profit. From a manufacturing standpoint, this requires the industry to resolve several important issues and to integrate them in a cohesive technology solution. This includes, but is not limited to:

a) a reliable method for placing and electrically interconnecting millions to tens of millions of µLEDs into an array configuration at a very high assembly rate (>100M units/hr) at high precision;
b) solutions for µLED testing before and after assembly and defect management after assembly;
c) at a wafer level, minimizing the component cost by eliminating those preparation steps that are not inherently required to fabricate an µLED.

Uniqarta's MLET technology holds the promise of solving these issues. Depending on the system configuration and panel size, the placement rates in MPLET can exceed 100M units/hr for large panels and 500M units/hr for small ones. Regarding placement precision, according to some authors, currently the mass manufacture of displays allows for a placement precision down to around ±34 µm, whereas µLED would require the precision to be narrowed down to around ±1.5 µm [10]. Recently, Uniqarta has demonstrated laser transfer of 50×50×6 µm µLEDs with an average placement error of 1.8 µm.

Defect management is an integral part of MPLET with its ability to screen out and replace defective µLEDs. Finally, MPLET works with µLEDs transferred directly from the substrates for epitaxial growth without the need to relocate µLEDs to a complementary source substrate as in the µTP methods.

5. Impact

Uniqarta's MPLET technology solves the problem of economically placing large quantities of µLEDs across a large area by increasing the placement rate of µLEDs to more than 100M units/hr. This capability, which also includes the ability to

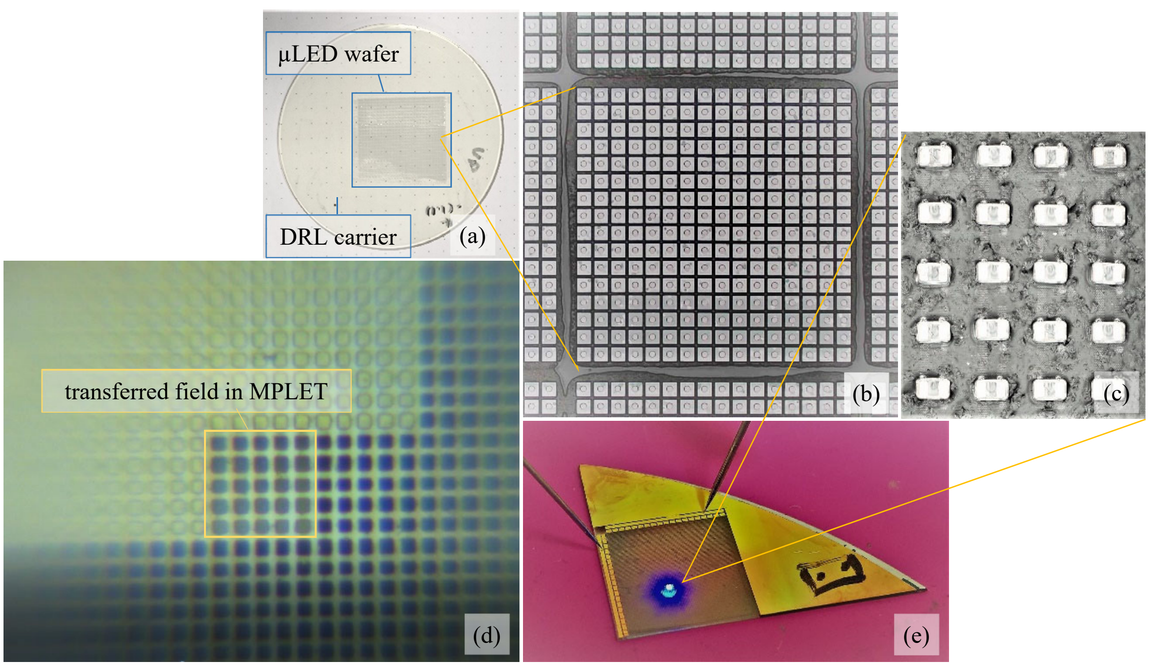

Figure 5. (a) A 2-in µLED wafer bonded to the DRL carrier, ready for laser transfer; (b) a close-up of the transferred µLEDs on the DRL carrier; (c) 55×32×6 µm µLEDs laser placed on a test substrate's bonding pads, ready for soldering (pads are not visible in this photograph); (d) a screen shot from an MPLET video clip showing a 5×5 array of 42×42×6 µm dummy dies immediately before laser transfer; (e) probing of soldered 55×32×6 µm µLEDs on a test substrate.

pre-screen and replace non-functional/subpar LEDs, reduces assembly times to minutes and enables market-compatible price points. This is a capability not commercially available today. Other approaches for high-speed µLED placement are being developed. However, none are reported to be capable of placement rates matching Uniqarta's solution nor deal efficiently with the problem of non-functional or subpar LEDs.

6. Acknowledgements

Author wants to acknowledge the support received from NSF (Awards Nos. 1519514, 1632387, and 1745903).

7. References

[1] Larsen, R. An introduction to Micro LED; a new self-emitting display technology. 2016 [available from: http://www.flatpanelshd.com/focus.php?subaction=showfull&id=1477048275].

[2] Acharya, A.R., Group III–Nitride Semiconductors: Preeminent Materials for Modern Electronic and Optoelectronic Applications. Himalayan Physics, 2015. 5: p. 22-26.

[3] Peddie, J., Augmented Reality: Where We Will All Live. 2017: Springer.

[4] Chu, R. Press Release: TrendForce Says Potential Scale of Micro-LED Market Could Reach US$30~40 Billion If It Was to Supplant the Current Display Chain. 2017 [available from: http://press.trendforce.com/node/view/2801.html].

[5] Jeon, C., H. Choi, and M. Dawson, Fabrication of matrix-addressable InGaN-based microdisplays of high array density. IEEE Photonics Technology Letters, 2003. 15(11): p. 1516-1518.

[6] Lee, V.W., N. Twu, and I. Kymissis, Frontline Technology Micro-LED Technologies and Applications. Information Display, December 2016, Iss. 6: p. 16-23.

[7] Park, S.-I., et al., Printed assemblies of inorganic light-emitting diodes for deformable and semitransparent displays. Science, 2009. 325(5943): p. 977-981.

[8] Bibl, A., et al., LED display with redundancy scheme. 2014, LuxVue Technology Corporation.

[9] Marinov, V., et al., Laser-Enabled Advanced Packaging of Ultrathin Bare Dice in Flexible Substrates. Components, Packaging and Manufacturing Technology, IEEE Transactions on, 2012. 2(4): p. 569-577.

[10] Golightly, D. Tech Talk: Where Are All Of The Micro-LED Displays? Android Headlines, October 17, 2017.