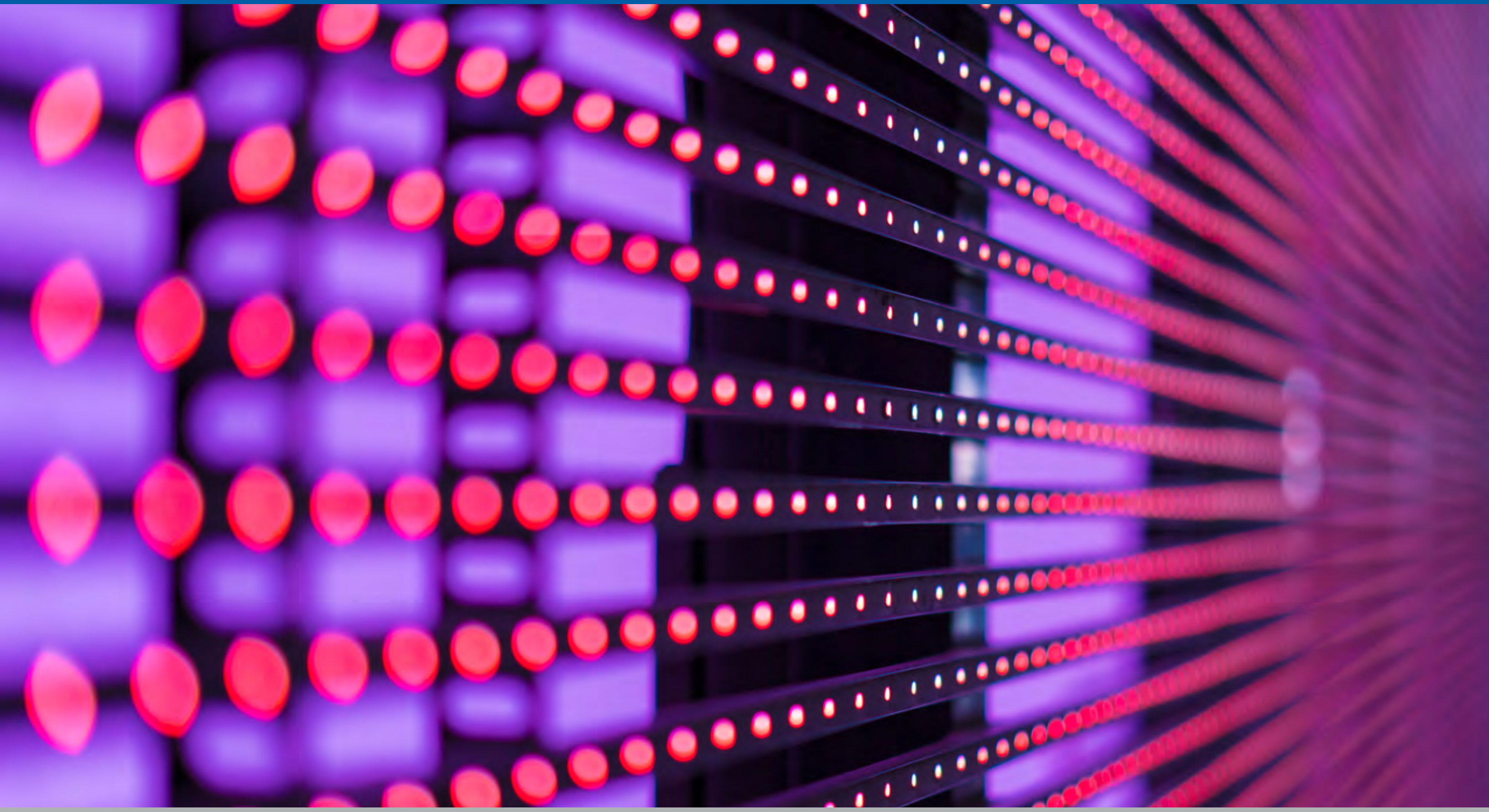
MicroLEDs – Laser Processes for Display Production



White Paper

High energy, ultraviolet laser beams enable the UV*transfer* process for display fabrication, specifically for laser lift-off (LLO) and laser induced forward transfer (LIFT) as well as pixel repair. This document provides an update including how UV*transfer* ensures these mass transfer and placement production steps will remain future-proof as die dimensions continue to shrink. Plus, the process offers the advantage of compatibility with various repair schemes to accommodate anticipated realistic die yields.

MicroLEDs – The Potential and the Challenges

MicroLEDs (μLEDs) represent an exciting emerging device type with tremendous potential for future displays. Typically based on gallium nitride (GaN), these devices currently have dimensions in the 20-50 μm range, with expectations that they will shrink to 10 μm and smaller. Using existing GaN fabrication technology on sapphire wafer growth substrates, μLEDs can be created in very high densities with street widths of a few microns.

The combination of micron dimensions, high brightness and high fabrication density can expand the display market beyond that presently enabled by OLED and LCD technologies. For instance, μLEDs can be used to create miniaturized (e.g., <1"), high definition displays for AR/VR applications. And, at the other end of the size spectrum, they support very large displays for indoor and outdoor use.

Such large displays can be fabricated economically from μLEDs, because as die size shrinks, the number of dies that be grown on a given sized wafer increases significantly. Consequently, for large displays, where pixel pitch is much larger than the die dimensions, the main display cost driver becomes the total number of pixels. This is in contrast to OLEDs and other technologies, where cost scales with total display area.

However, there are several technical challenges to overcome prior to widespread deployment of μLEDs. One key hurdle is developing a process to release the dies from the sapphire growth wafer. Another is a process to transfer these to the display substrate with micron level precision and reliability. And, these processes must be compatible with repair/replacement schemes to address the inevitable issue of defective dies. At the same time, they must be compatible with automation and deliver high throughput as the LED industry targets up to a 20X reduction in current overall costs. Moreover, the expectation of a continuous trajectory of ever smaller dies will favor processes that accommodate this miniaturization trend without the need for capital intensive retooling for each successive size reduction.

> "...a continuous trajectory of ever smaller dies will favor processes that accommodate this miniaturization trend."

Figure 1: Illustration of a Large Direct View MicroLED Display.

Laser Processing Context

Laser processing based on high energy ultraviolet laser pulses with nanosecond pulse duration offers a unique combination of advantages to meet these challenges. Short wavelength UV light can directly ablate thin layers of materials at interfaces and surfaces without penetrating deep into the material. In combination with the short pulse width, this cold photo-ablation process avoids inducing thermal shock and damage to underlying material. And the large pulse energy uniquely offers a ***multiplex*** process advantage because the beam can be used to project a photomask, enabling hundreds and even thousands of dies to be processed with each pulse. That's why these types of lasers are well-established in the display industry as the mass production tool for generating the TFT silicon backplane for both OLED and high-performance LCD displays – a function they will undoubtedly continue with the next-generation µLED displays.

At this time, laser processing offers several opportunities for µLED display production:

- Laser Lift-Off (LLO) to separate the finished µLED from the sapphire growth wafer
- Laser Induced Forward Transfer (LIFT) to move the µLED from a donor to the substrate
- Laser repair of µLEDs to address yield issues and defect rates
- Excimer Laser Annealing (ELA) to fabricate a LTPS-TFT backplane
- Laser cutting at various levels of aggregation

Here are recent key developments in some of these areas.

Laser Lift-Off (LLO) Update

Laser Lift-Off (LLO) to separate finished µLEDs from the sapphire growth wafer has been described previously in *Laser Processing of Micro-LEDs*. So, here we only briefly review the main advantages of LLO for blue and green dies, including the latest automated alignment capability that is now part of the developmental tooling.

Bulk GaN µLEDs are typically fabricated on sapphire as the optimum growth substrate. But the thin LEDs must then be separated from the sapphire to allow creation of a second contact for vertical LED operation. Plus, the sapphire is impractically bulky for downstream processing, at 50-100X the thickness of the µLED dies. This creates a need to move high density µLEDs from the sapphire substrate and transfer them to a temporary carrier.

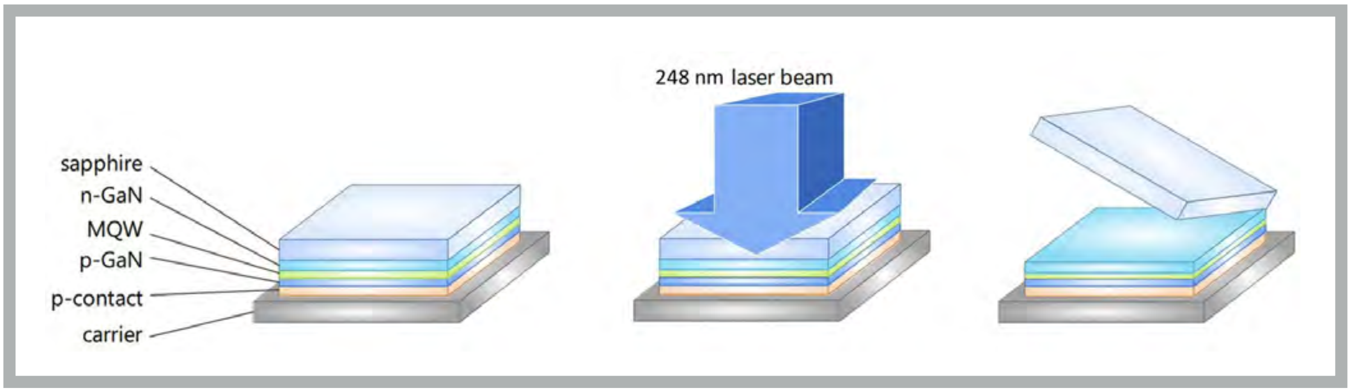


Figure 2: Schematic of a LLO process for the delamination of GaN film from sapphire wafer.

For the LLO of µLED Coherent has developed the UV-*transfer* process. The LLO process works by irradiating the dies from the rear surface (through the transparent sapphire). This ablates a microscopic layer of GaN, creating a small amount of expanding nitrogen gas that releases the die. The (248 nm) wavelength of our UV-*transfer* process also enables its use with µLEDs grown with some other material variants including AlN.

In the UV*transfer* process, the UV laser beam is reshaped to a rectangular beam with a "top hat" intensity profile before projecting on to the sapphire wafer through a photomask. This uniform intensity ensures identical force is applied at every point within the process field. The optics are configured so that a large area of dies is lifted with each high-energy pulse. This multiplex advantage is unique to our LLO using the UV*transfer* process based on high energy, UV excimer laser pulses, and will be a critical enabler, supporting reduced costs in high volume production. (A similar system from Coherent called UV*blade* is now widely used in LLO for flex OLEDs).

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Excimer-based LLO systems are already in operation in several µLED pilot product lines. Initially motion of the wafer relative to the projected (masked) beam was controlled solely by the encoders on translation stages. "On-Die Processing" is a recent advance and the core of the UV*transfer* process that now further improves alignment precision, thus enabling smaller dies and narrower streets.

"On-Die Processing" also eliminates the possibility of partially illuminating a die on the edge of the laser line. In this case, coarse alignment is still monitored by encoders on the translation stage. But fine alignment is implemented with a closed loop, smart vision system that aligns the wafer relative to the beam using the checker-board pattern of dies. This ensures the edges of the laser field always coincide with the middle of a street and never across a die.

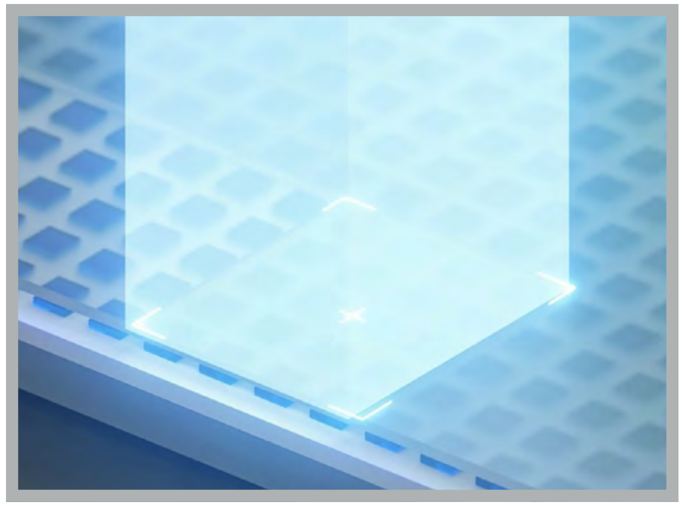

Figure 3: In the UV*transfer* process, the on-die processing feature ensures that the edges of the laser field always coincide with the middle of a street.

Laser Induced Forward Transfer (LIFT)

The UV*transfer* process is also a perfect fit for the mass transfer and placement of selected dies using the principle of Laser Induced Forward Transfer (LIFT). Here a key challenge is the dramatic difference in pitch. On the wafer and the transfer carrier, the dies are closely packed, currently with a pitch of around 1000 dpi. But depending size and resolution, the pitch might be only 50-100 dpi on the display. Plus, the dies must be interleaved, with a red, blue and green die placed in each pixel location.

Existing non-laser transfer methods cannot deliver the necessary throughput at the required resolution. For example, mechanical pick and place methods are limited in speed and placement accuracy, and therefore cannot support the current technology trajectory. On the other hand, flip chip bonders are capable of high accuracy placement (e.g., ±1.5 µm) but can only handle one die at a time. In contrast, UV*transfer* can deliver both high (±1.5 µm) accuracy and massive multiplex throughput, moving and placing thousands of dies in a single laser shot.

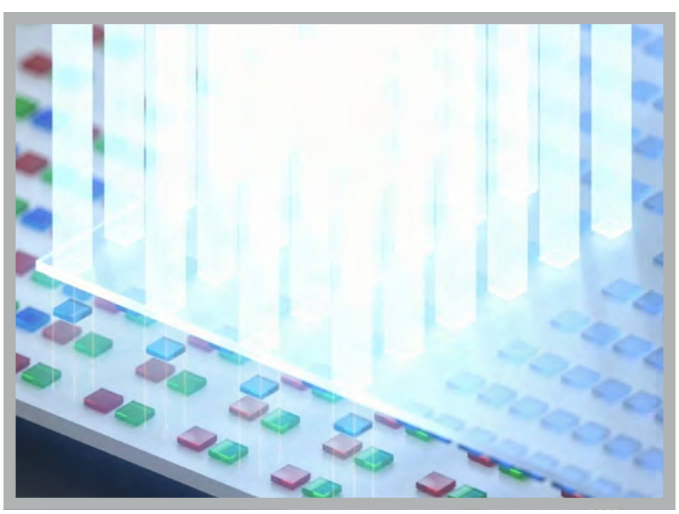

Figure 4 shows schematically how this method operates. LLO leaves the dies attached to a temporary carrier by means of a dynamic release layer. This is a benign adhesive that strongly absorbs UV light. The temporary carrier and dies are placed in near-contact with the final carrier, which is usually a glass or flex panel already patterned with a TFT backplane and covered with a bonding layer or pads. The UV light is directed from the back of the carrier. Virtually all the laser energy is absorbed by the dynamic release layer that is thereby vaporized. The impulsive force due to the expanding vapor pressure propels the die from the carrier on to the final substrate ideally without residues on the dies.

Figure 4: UV*transfer* uses a step and scan process with a mask in order to create the correct pitch on the display.

Unlike the LLO process, where entire areas of adjacent dies are simultaneously processed, the transfer process is the step at which the pitch of the dies is changed from the close separation of the original wafer to the pixel pitch of the final display. This is performed using a photomask with a pattern that only irradiates every 5th die or every 10th die, for example. When the next area of the display is then translated into position for filling with dies, the mask is indexed to move one unit of the wafer pitch, relative to the temporary carrier, enabling a whole new array of dies to be transferred.

Another difference between LLO and transfer is that the latter involves ablation of an adhesive, requiring 5-20X lower laser fluence than a III-V semiconductor. This high efficiency means that high throughput can be achieved with only modest laser powers.

Several other features of our UV*transfer* process are key to its implementation. For instance, even though the gap between the carrier mounted dies and the TFT- substrate is near zero, the impulse force must be managed and controlled in order to achieve successful transfer of every die, with accurate placement and no damage. Specifically, both the magnitude of the force and the direction of the force must be optimized and consistent over the entire display in order to not compromise the process window for the transfer.

Highly uniform and consistent transfer of the dies in the process field demands highly uniform laser irradiation which is a core competency at Coherent that is widely used in diverse applications. This creates a highly uniform 2D field which is then optically reshaped into a square or rectangle with high aspect ratio, in order to match the application. For the transfer of 6" wafers for example, the usable field on the wafer is around 100 mm x 100 mm. As illustrated schematically in figure 4, having intensity uniformity on the local (single die) scale means the die is pushed equally across its entire area. Thus, the force is always perpendicular, with none of the lateral shifts that would be induced by a beam with a gaussian or sloped intensity profile. Having a homogeneous beam intensity on the larger (wafer width) scale is equally important, as this ensures that each die is pushed with the same force magnitude.

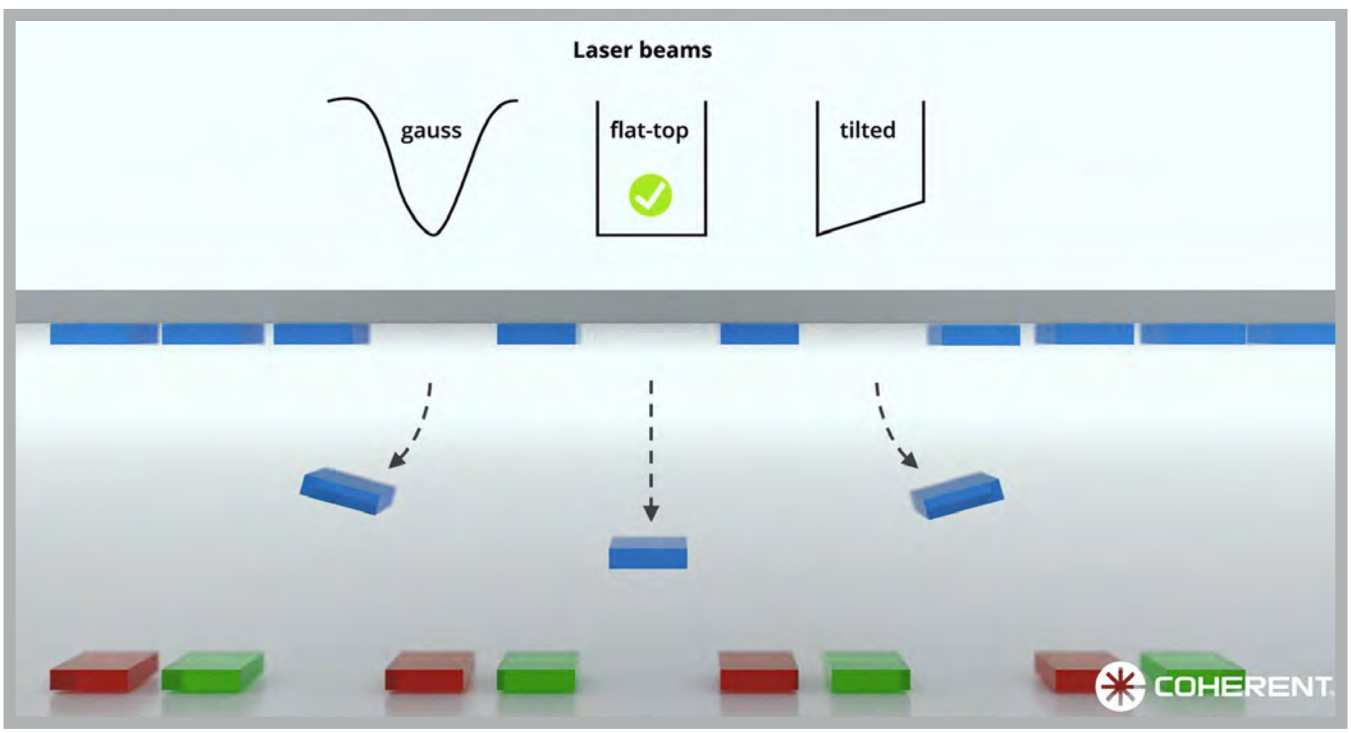

Figure 5: A highly uniform "flat top" beam profile is essential for accurate placement – not to scale.

Importantly, the UV*transfer* process can easily support much smaller dies (<5 microns) and narrower streets than currently in pilot production. Indeed, future micron scale resolution is achievable because of the short UV wavelength. All that is required for smaller dies is a different projection mask.

Repair/Replacement of Rogue Dies

The market success of displays based on µLEDs requires both a major reduction in production costs and a relentless push towards 100% yields. Otherwise, displays with potentially hundreds of millions of pixels will not be practical. But problem dies are inevitable, so manufacturers can only adopt production technology platforms that are compatible with repair/replacement schemes. Coherent's UV*transfer* applied to both LLO and transfer is compatible with replacement concepts that are already being investigated.

The first step in this process is locating and removing bad dies from the wafer. But, this then leaves missing spots (that would have been occupied by the removed dies) on the temporary carrier. So, these empty spots must then be refilled on the final substrate.

The failed dies can be removed from the wafer before LLO, by applying the process to a selected area only, down to a single die. The map of removed dies from each wafer is then transferred forward and turned into a map of missing dies on the substrate. These can be individually inserted after mass transfer by a similar forward UV*transfer* process, but this time using a defined single ultraviolet beam. The laser power is matched to whether the laser is ablating a III-V material or a sacrificial adhesive.

Summary

MicroLEDs represent an exciting developing technology that can expand the performance and applications for displays at both ends of the size spectrum. No one doubts that there are numerous hurdles to overcome before high throughput becomes a production reality. But two highly multiplexed processes using UV laser beams are demonstrating their capabilities at the pilot plant level. More importantly, UV*transfer* is completely size-scalable enabling a smooth forward journey along the miniaturization road map, without the need for costly re-investment or process replacement at any point. Once the customers process is developed the demonstrated solutions can be easily transferred to production lines due to the high energy UV laser scalability but keeping the precision of todays and tomorrows requirements.

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