Laser Processing of Micro-LED

The speed of innovation and technology development for advanced display products is breathtaking. While large-scale investment in OLED display production is ongoing in Korea and China, there is already a new technology that may challenge LCD and OLED displays in some segments. Specifically, displays comprised of micro-LEDs (µLED) are stepping up to this challenge.

Micro-LEDs based on inorganic III-V semiconductors (such as GaN) hold great promise for displays that outperform existing technology in terms of efficiency, brightness, pixel density, lifetime and operating range. Moving from LED (~200µm) to µLED (~20µm) demands technical innovations; assembling µLEDs into a display raises many technical challenges, and hence, creates opportunities for laser-based processes.

Laser processing is at the forefront of technology in the display industry; lasers enable mass production of the most demanding tasks. They enable the "perfect" cutting of substrates, fine patterning, low-temperature polycrystalline silicon (LTPS) annealing, temporary carrier delamination (laser lift-off) for flexible displays, and more.

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
- Excimer Laser Annealing (ELA) to fabricate a LTPS-TFT backplane
- Laser cutting at different levels of aggregation
- Laser repair of µLEDs to address yield issues and defect rates

Coherent pioneered the LLO and LIFT laser applications. This paper describes them in detail.

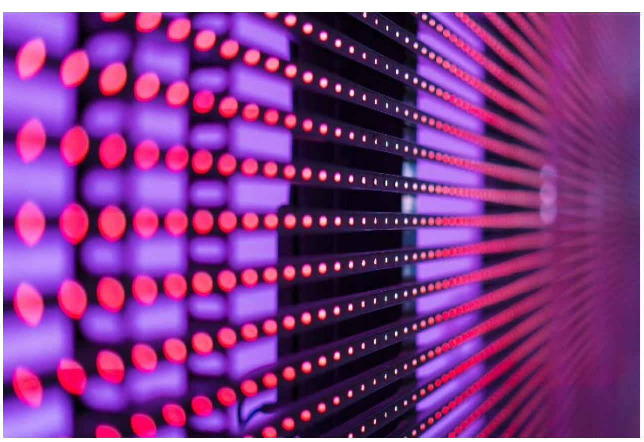

Figure 1: *Large direct view display assembled from individual LEDs.*

Laser Lift-Off

Bulk GaN substrate wafer manufacturing is difficult, and not applicable to commercial LED production. Instead, GaN layers are heteroepitaxially grown on dissimilar substrate materials such as sapphire, silicon carbide (SiC) or silicon. The vast majority of LED production today utilizes sapphire wafer as the growth substrate for the MOCVD due to its small lattice mismatch and relatively low cost. However, as a final carrier material it severely hampers the performance of the GaN LED. The low thermal and electrical conductivity of sapphire as a device substrate restrict the extractable luminous flux of an LED for two reasons: 1. In a sapphire based LED design, efficient dissipation of the heat generated by the LED drive current is strongly inhibited due to current crowding; 2. The contacts must all be connected to the front-side of the LED resulting in unfavorable light emission characteristics during operation. Hence, a widely accepted route in HB-LED development and manufacturing is integration of GaN layers with dissimilar host substrates through wafer-bonding, and subsequent non-contact sapphire delamination via LLO. For µLEDs it is easy to see that the sapphire must be removed to end up with thin devices that will comprise flexible displays. The following schematic shows the basic process.

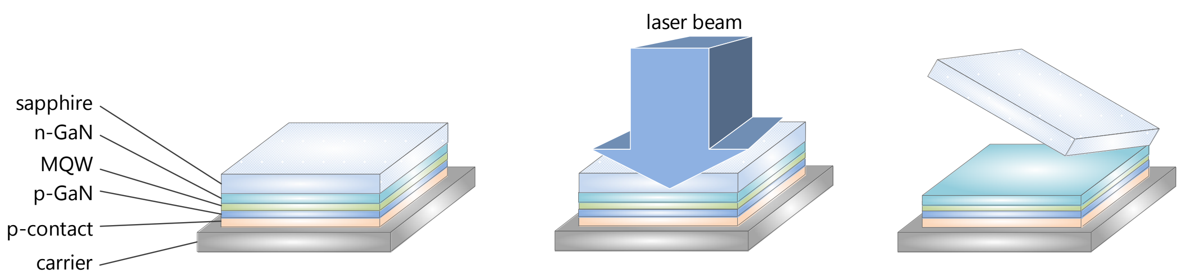

Figure 2: *Schematic of a LLO process for the delamination of GaN film from sapphire wafer.*

The µLEDs are processed on the sapphire growth substrate to the level that a temporary or final carrier substrate is attached. In the subsequent LLO process, the LED wafer is exposed to high intensity UV laser pulses directed through the sapphire substrate, which is transparent at a wavelength of 248 nm. The interfacial GaN layer absorbs the UV laser photons, heats up to about 900°C and undergoes thermal decomposition. The thermal decomposition of GaN during the LLO process involves the formation of nitrogen gas and metallic gallium according to the following chemical reaction:

$$2GaN(s) \rightarrow 2Ga(l) + N_2(g) \qquad (1)$$

The affected zone is minimized and controlled by the fluence of the laser beam; typically at that interface, around 10 nm of GaN is ablated and changes to liquid gallium and nitrogen gas. The sapphire wafer is then easily removable with nearly zero force exerted on the devices. The gallium may be washed off by water or diluted HCl acid to leave a clean surface on the device.

One important consideration for this process is the choice of the laser wavelength, it must pass through the sapphire and then have minimal penetration into the device structure. For the GaN, InGaN materials, the 248 nm wavelength of excimer laser (5 eV) is a perfect choice; it exceeds the bandgap of GaN (3.3 eV) but experiences no absorption in sapphire. Some material combinations, such AlN with larger bandgap, may be processed using a 193 nm excimer laser.

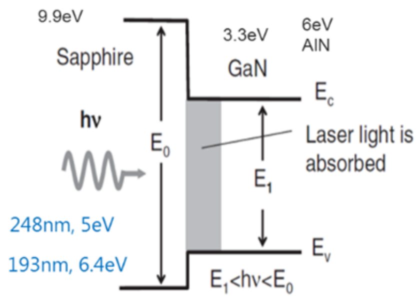

Figure 3. *Bandgap of GaN, AlN and sapphire. The photon energy of the excimer laser is referenced in blue.*

Using short laser pulses minimizes heat diffusion and reduces the stress on the device layer. The typical excimer laser pulse length of 10-20 ns is perfectly suited to this need. It suppresses thermal diffusion and minimizes heat load on the device. LLO is in essence a one-shot process which sets a high demand on beam uniformity and laser stability. With the excellent pulse to pulse stability of the excimer laser (< 1% rms), nearly perfect process control is achieved by providing a large process window. The beam on the wafer must provide the same fluence over its whole cross section – a flat-top beam is required. Furthermore, the exact shape of the beam hitting the wafer in the LLO process must be optimized within the context of the overall process strategy and the wafer size.

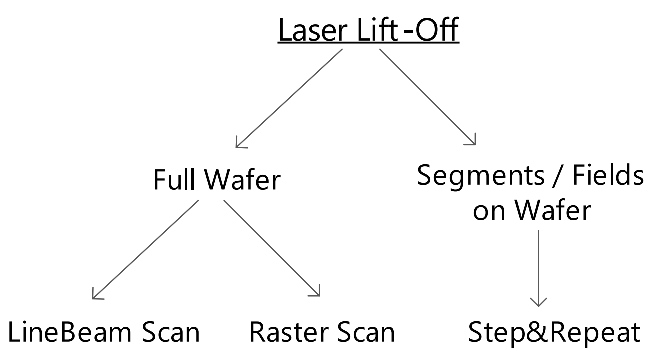

Figure 4. *Process strategies for LLO.*

As shown in figure 4, the LLO process can be used to separate the entire wafer or only smaller fields of interest. To remove the entire sapphire wafer from the device layer, two different process strategies are applied, namely LineBeam Scan or Raster Scan. Like most excimer laser applications, LLO also uses a stationary beam in combination with a moving substrate that is precisely positioned by an x,y,z stage. For the best trade-off between throughput, quality and cost, Coherent offers different system configurations to ideally match the customers' needs.

For high throughput, the laser beam is formed into a line beam that can cover the complete sapphire wafer (2", 4" or 6") in a single scan. In our UVblade LLO systems, the line beam is shaped into a uniform top-hat profile with a uniformity of better than 2% sigma to ensure uniform interaction in the process. This setup, in combination with the output power (e.g. 100 W, 248 nm), delivers the highest throughput. Moreover, using a beam that covers the entire wafer leads to a uniform process: Intrinsic stress in the film stack that may come from CTE mismatch is uniformly released, which further reduces the impact on the devices. For these reasons, the line beam scan is the preferred embodiment for full wafer LLO with a requirement for high throughput. UVblade systems cover today's typical wafer sizes, and up to 155 mm line length is installed in pilot production today with a roadmap to 8" and more.

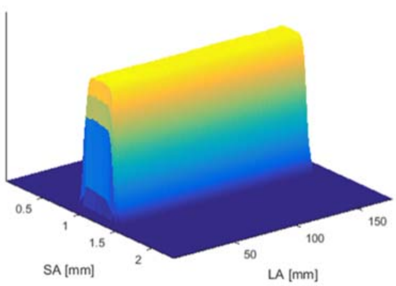

Figure 5. *Beam profile of the 155mm LineBeam of the UVblade @ 248 nm with short axis (SA) and long axis (LA). Note the two orders of magnitude difference in the axis scales.*

As shown in figure 5, the UVblade LLO system generates a top-hat beam in the short axis (~0.5 mm) and the long axis (155 mm). This ensures that all of the process area is exposed to the same optimum fluence. UVblade systems avoid the energy overshoot or unwanted heat load that is typical for processing with Gaussian beams.

Figure 6. *UVblade LLO system with LEAP excimer laser and line beam optics.*

Another optimized strategy for this process is to use a smaller size beam and raster scan that across the wafer. In this case, special consideration is given to the shape and size of the beam in order to match with the laser and the device wafer. A typical beam shape as used in our UVblade system is e.g. 26 mm x 0.5 mm, which covers a 2” wafer in only two scans and takes four scans for the commonly used 4” wafer. With a laser power of 30 W at 248 nm, these systems already reach a high throughput since the laser processing takes only 10 seconds per 4” wafer. With higher power and a larger beam size e.g. 52 mm, higher throughput is achieved. High uniformity in the beam ensures a large process window and a uniform process. The raster scan approach demands the controlled stitching of the individual shots in the scan direction as well as the stitching between the scans. Obviously, a gap in the stitching area, or too much of an overlap, should be minimized.

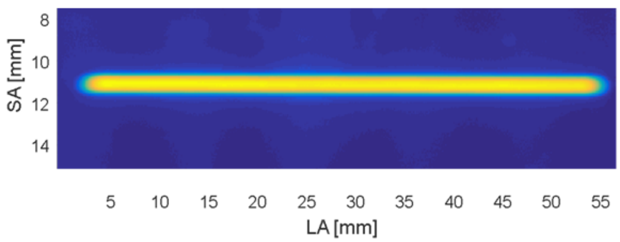

Figure 7. *Typical beam profile for Raster Scan.*

Figure 7 shows a measured beam profile for the 248 nm beam line of the UVblade. The line length (LA) is 52 mm and the width in the short axis (SA) is about 0.5 mm. The use of high grade UV optical materials and beam homogenization in both axes gives high uniformity of <2% in the flat-top beam area. Special attention has been spent on the exact shape of the beam and the steepness of the profile in order to minimize the impact to the sensitive film structure and support seamless stitching without artefacts.

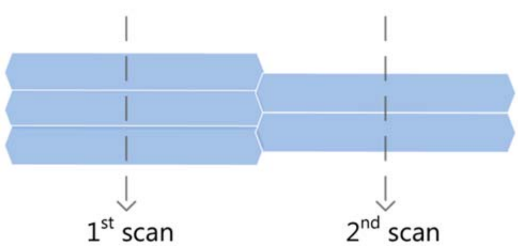

Figure 8. *Stitching of fields.*

In figure 8, a possible strategy for stitching of the fields is sketched. The beam may be shaped like a chevron in order to minimize the stress on the film structure and get optimum results over larger wafer areas.

Laser Induced Forward Transfer

The assembly of a high resolution display from many million µLED chips presents its own challenges. Lasers have been studied for this application for many years. Here we describe the concept of using an excimer laser beam to induce the separation of selected µLEDs from a carrier and then transfer them to a receiving substrate. As described for the LED LLO process, the 248 nm wavelength is perfectly suited for precise ablation of GaN. The process generates some nitrogen gas, which expands and induces mechanical force on the µLED structure that pushes the chip from the carrier to the receiving substrate. Using the large beam cross section enabled by the excimer laser as shown in figure 6 (52 mm x 0.6 mm), in combination with a mask and projection optics, allows transfers of up to 1000 dies in parallel with a single laser shot.

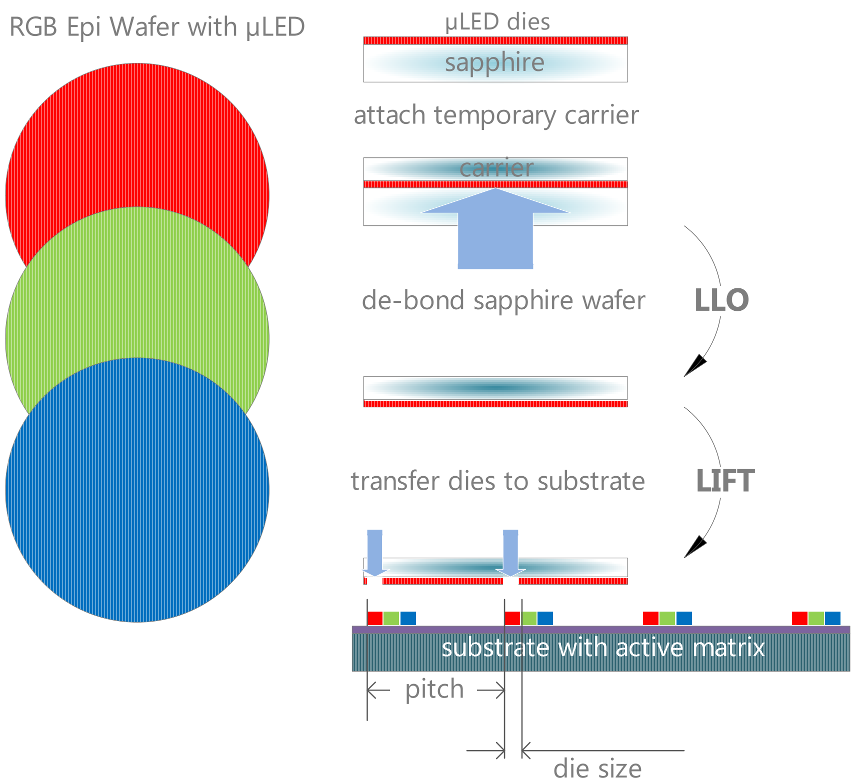

Figure 9. *Sketch for µLED assembly using LLO and LIFT.*

In a variation of the process, the µLED may also be preassembled on a temporary carrier wafer or tape by using polymer based adhesives. One characteristic of these adhesives is strong absorption in the UV. Irradiation with a wavelength of 248 nm or 308 nm will induce photo-chemical decomposition of the adhesive, which releases the µLED chip and also induces forces to push the die to the receiving substrate. The energy density that is required to initiate the release from a polymer tape or adhesive can be 5-20 times lower than the required fluence to separate the inorganic III-V semiconductors. This means that very high process speeds can be achieved with moderate laser powers.

In summary, excimer lasers have excellent potential for emerging laser applications in the µLED space. Their unique characteristics such as short UV wavelength, and short pulse length, combined with high energy and power, are well suited for the III-V material systems commonly used in LED manufacturing. The 248 nm excimer in particular far exceeds the performance of 266 nm or 213 nm solid-state lasers. Given this, the excimer enables significantly differentiated process strategies that are highly productive, and therefore cost effective.

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