Engineered Substrates for High Efficiency MicroLEDs and Commercialized High Volume Manufacturing Production

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There is a tremendous growing interest in MicroLEDs as the next-generation display technology. But there are some technology issues that must be addressed before MicroLEDs become commercially viable or mainstream. QMAT EpiMax™ engineered substrates address the form factor and function of MicroLEDs for high brightness and performance along with a wafer carrier function to provide a HVM (high volume manufacturing) production path for high volume electrical test and mass transfer technology.

The competing technologies to MicroLEDs are in flat-panel and organic light emitting diode (OLED) displays. MicroLEDs win over flat-panel display technologies in the area of low power, high brightness, ultra-high definition, high color saturation, faster response rate, longer lifetime, and higher efficiency. Whereas, OLED technologies are plagued with yield, cost, and display lifetime issues.

MicroLEDs can be used in most mainstream applications such as monitors, wearable devices, AR/VR, mobile phones, tablets, laptops, monitors, and TV displays. Due to its attributes of low power requirements, high brightness, and a wider operating temperature there is high interest in the area of automotive and industrial applications. As a disruptive technology it has the potential to replace the TFT-LCD market.

QMAT EpiMax™ engineered substrates can help solve current MicroLED manufacturing issues which are summarized below:

1) Lower quantum efficiency as devices shrink in size.
2) Long MOCVD reactor time, 6 – 8 hours.
3) No test or print assembly features on current MicroLED substrates.
4) Non-contact electrical test for MicroLEDs is not available. Current non-contact Photoluminescence (PL) is being researched, but no correlation has been established while the direct contact method is not scalable.
5) Pick and place technologies for either die or stamp type mass-transfer are currently too slow.

High peak MicroLED efficiency has been shown to be achievable down to 10µm x 10µm device size, however the peak values occur at current density values in A/cm2, substantially higher than the expected display operating points [1]. At a current density range of 1-1000 mA/cm2, traditional growth substrates can have low efficiency due to a higher value of its non-radiative recombination parameter "A" in the ABC model of recombination. Non-radiative recombination is related to total threading dislocations (TTD) and low-dislocation GaN material has been shown to improve device performance and limit non-radiative recombination under low injection conditions [2]. The engineered substrate approach can thus improve device efficiency and limit variability at the desired current density operating point by using high-quality GaN as a seed layer for MOCVD growth.

The typical die size of a MicroLED is <100µm X 100µm trending down to <5µm X 5µm. As die sizes shrink, external quantum efficiency (EQE) drops (see Figure 1) and can only be recovered through better quality GaN (low dislocations/pixel).

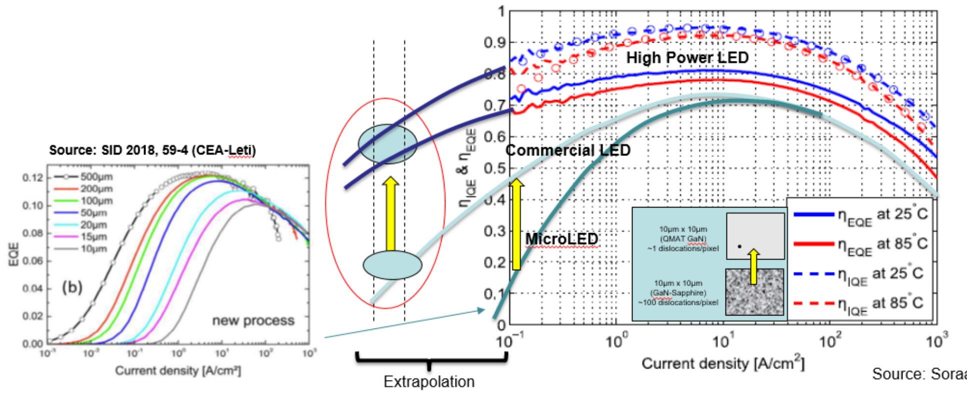

Figure 1: EQE (FS-GaN High Power & GaN on Sapphire Commercial and Micro-LED)

In the manufacturing of MicroLEDs the challenges are the high cost, die yield variability during process and die transfer to the display. The high cost can be attributed by the use of low defect material, the lack of testability of die prior to placement of the MicroLEDs onto the display, resulting in the need for repair (due to blind printing), and the mechanics of die placement.

Through QMAT's layer transfer technology, all sizes of expensive high quality III-V wafers can be effectively utilized by making multiple engineered substrates equivalent to the original donor substrate (see Figure 2).

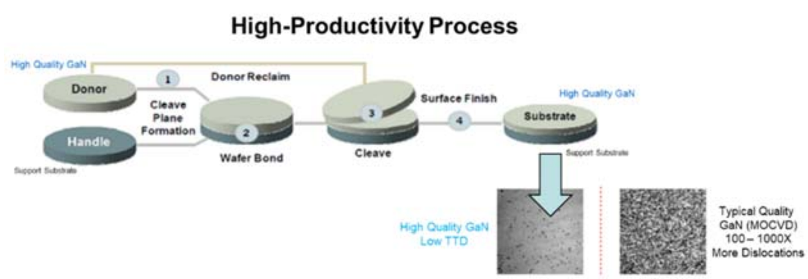

Figure 2: QMAT III-V Layer Transfer Technology

QMAT's technology enables the integration of proprietary functional layers into the final product substrate for the use as a transfer layer release through laser ablation and/or as an electrical test enhancement layers (see Figure 3).

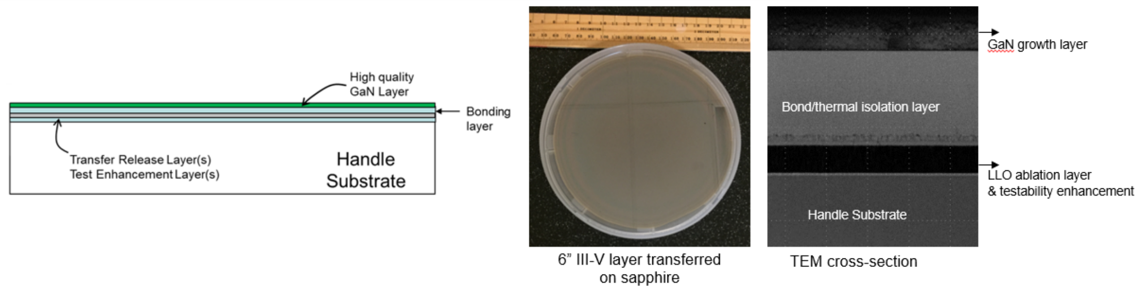

Figure 3: Functional Transfer and Test Enhancement Layers

The QMAT EpiMax™ engineered substrates have the following advantages:

1) High quality GaN films improving device performance and reducing the overall cost of the substrate used for manufacturing LEDs.
2) Reduction in MOCVD growth time >2X in the manufacturing of the LED structure reducing growth cost.
3) The Epi substrate can be tested for individual die quality after LED fab with a generated map of known good die (KGD) preventing the transfer of bad die to the display.
4) The Epi substrate can become a print head for selective mass transfer, much more efficient than a pick and place strategy.
5) The functional layer is an integrated "Laser-Lift-Off (LLO) layer between a transparent substrate and the thin Epi-ready GaN surface. The LLO ablation process can now be performed in a softer "LLO" process due to individual die isolation thus avoiding device degradation (minimizing a higher parameter A) [3].

QMAT has also developed a corresponding "Transfer or Carrier" wafer. The carrier wafer can be integrated with common LED fab processes. Conventional LEDs can be transferred to the carrier wafer resulting in a final substrate comparable to LED wafers using QMAT's engineered substrates which now can be electrically tested and mass transferred. A general manufacturing comparison of the two types of LEDs is shown in Figure 4 below.

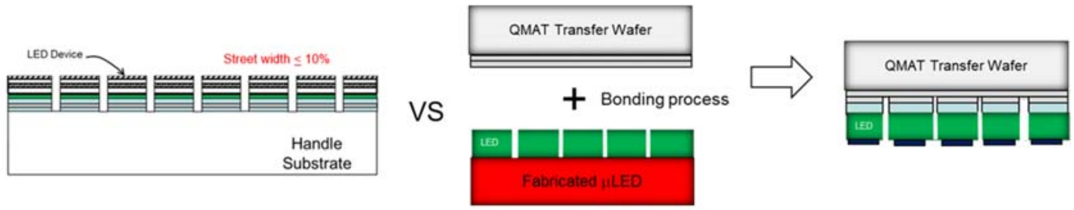

Figure 4: MicroLED with QMAT Epi Substrate Vs.
Conventional LEDs on QMAT Transfer Wafers / Non-Epi Substrate

The importance of testability can been seen for the following relationship of yield. The generally accepted display yield equation is: $Y = (1\text{-}D)^{\#pixels}$, where D is the defect rate and #pixels is the display pixel count. For our discussion, D is composed of defects from the substrate (D_{sub}) and epi (D_{epi}). Through testing (D_{test}): $D = D_{test}\,(D_{sub}) + (D_{epi})$. For 4K UHD resolution there is approximately 25M microLED pixels required. If the overall display assembly build was 95% and defects related to assembly was zero, the MicroLED defect contribution from the substrate and epi processes would be approximately 2ppm [4]. It is unrealistic to believe the total combination of substrate and EPI defect rates of III-V compound semiconductor materials and physical processes such as MOCVD growth could achieve a process defect rate at this level or less. This can only be achieved by in-process testing.

The concept of using the QMAT GaN-on-Sapphire engineered substrate as a "print head" for mass-transfer assembly of MicroLEDs for displays is shown below in Figure 5.

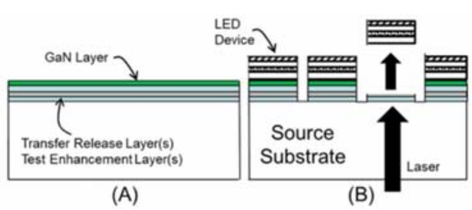

Figure 5: QMAT EpiMax™ Substrate for GaN MicroLED Manufacturing (A= Growth Substrate, B= after LED Epi Growth).

Figure 5 is an illustration of a QMAT engineered substrate (Figure 5A) that is processed and patterned into a substrate of MicroLEDs (Figure 5B). By using a transparent source substrate such as double-side polished sapphire, a laser beam can be directed through the back of the source substrate, impinging on the release layer thereby releasing or printing a MircoLED onto a target display plate in a very fast manner using a back-illuminated beam addressing method. The key feature of this approach is the "Soft Laser-Lift-Off" (SLLO) between the sapphire substrate and thin Epi-ready GaN surface which avoids damage to the MicroLED chip.

In summary, the advantages of utilizing QMAT EpiMax™ engineered substrates as a micro-LED source substrate are:

1) High Quantum Efficiency LED based on low TDD GaN layer transfer.
2) Lower MOCVD process reactor time by >50% at equivalent efficiency due to the reduction or elimination of the hetero-epitaxial buffer transition layer and the device is to be operated in a low current injection regime, process complexity and time can be substantially reduced.
3) Manufacturability and product improvements through the use of a functional layer for testability and a more efficient method of die placement.
    a. Individual die testing with a common conduction layer inside the bonding layers.
    b. Soft laser-lift-off approach using the engineered substrate as a print head for die placement.

On-going development on enhancement to the engineered substrates are in the area of:

1) Controlled micro pitch (less than 10%, i.e.: 10µmX10µm LED with a 1µm street).
2) Minimize side wall loss in ultra-fine MicroLEDs (<10µmX10µm)
3) Optimizing LLO process when used as a printer head.

Through the use of QMAT's EpiMax™ engineered substrates improvements in manufacturing yields, final product quality, and product specifications (better display uniformity, higher efficiency, longer battery life) can be realized. Development of QMAT's engineered substrates and carrier wafers continues by working with partners in product design, final test and manufacturing of MicroLEDs, bringing this technology from R&D mode to pilot production and finally into HVM production.

References:

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