Novel In-Process Functional Test Equipment to Enable MicroLED Mass-Production

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Objective and Background

Tesoro Scientific (Tesoro) is developing a novel EL test approach to enable cost-effective microLED manufacturing by recognizing that new process steps specific to microLED must be compatible and designed with the complete process in mind.

To better understand how Tesoro EL test technology can enable cost-effective microLED mass-production, it is important to understand the five new steps required within the microLED manufacturing process. Figure 1 shows a simplified block diagram of a microLED manufacturing process. The new steps are highlighted in green. They consist of (1) the EPI growth substrate, (2) the LED processing by material deposition using an MOCVD reactor, (3) a "Known Good Die" (KGD) test step, (4) the mass-transfer or printing of the microLED devices onto the display backplane, and (5) the microLED connection step to complete the device integration.

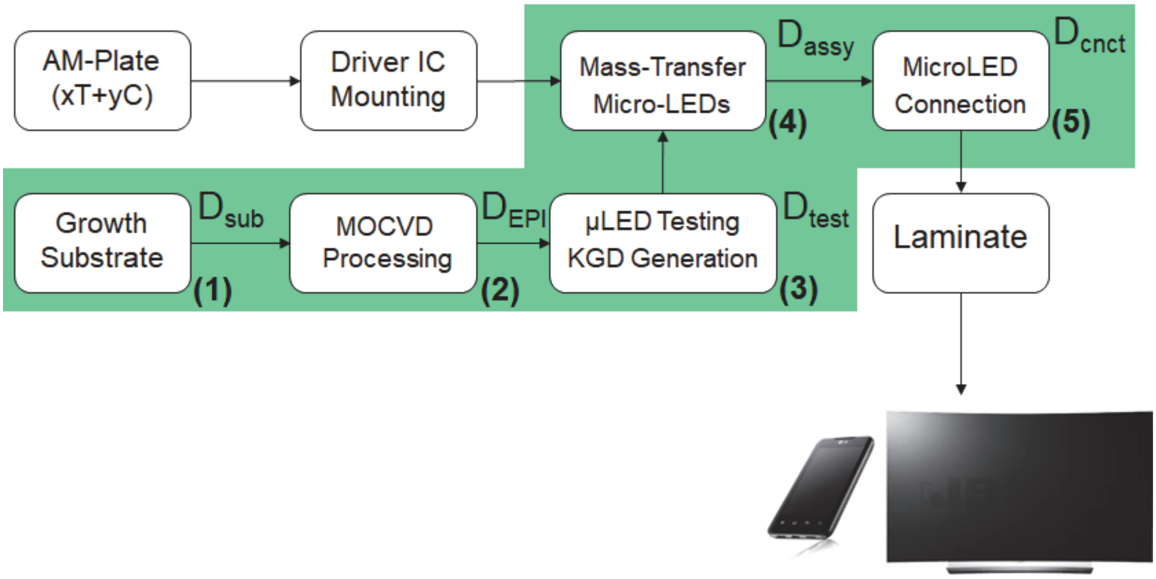

Figure 1. MicroLED manufacturing process sequence.

MicroLED Manufacturing Challenges

The basic issue in achieving cost-effective high-volume manufacturing of microLED displays are threefold:

a. The high cost and variability of the microLED devices and print processes.

b. The lack of manufacturing technologies necessary to test, "print", and interconnect these devices reliably on the display surface.

c. Low microLED efficiency at the 5-50um form factor.

These barriers are interrelated and can be successfully addressed by integrating novel materials and applying new manufacturing steps within the display productions processes.

Yield Analysis of the MicroLED Process

An analysis of the interactions of the various steps within the microLED process sequence can determine the main contributors to display yield. The display yield equation can be further simplified by assuming the individual step defect rates D_n shown in Figure 2 are low (less than a few percent) and each defect is a microLED killer defect. The microLED defect rate is thus:

$$D = D_{test} (D_{sub} + D_{EPI}) + D_{assy} + D_{cnct} \quad (1)$$

Where the individual process step defect rates are defined as:

D_{test} : In-process microLED test (false positive)

D_{sub} : Substrate defects (~10ppm for 10µmx10µm microLEDs)

D_{EPI} : MOCVD EPI & LED processing (~ 100-1000ppm)

D_{assy} : Mass-transfer/assembly process (method dependent)

D_{cnct} : Connection process (method dependent)

The overall display yield is:

$$Y = (1-D)^{\#pixels} \quad (2)$$

Where #pixels is the display pixel count.

MicroLED Manufacturing Improvements Using EL Functional Test

Currently, microLED processes and manufacturing equipment either do not exist or are in early stages of development. Although some proposed approaches were successful in their original applications, they may be difficult to adapt for microLED applications and can be incompatible with other steps to achieve high-yield at a high manufacturing production rate. In-process functional test capabilities of source microLED devices is one such element. The test methods developed for large device LED lighting use electrical probe pins and cannot be scaled to measure micron-sized microLED structures that often have missing contacts and number in the hundreds of millions on one source substrate.

The following introduces a comprehensive approach to microLED manufacturing where new processes and equipment capabilities within the five process steps are made to work synergistically to improve overall microLED manufacturing yield and throughput.

Source Substrate of MicroLED Devices for EL Functional Test

To achieve high-yield manufacturing, a MicroLED source substrate must allow EL in-process functional test and rapid mass-assembly specifically tuned for microLED display fabrication.

While a variety of EL test compatible source substrates are possible, Figure 2 shows a source carrier substrate made to be used as a “print head” for mass-transfer assembly of microLEDs for displays. This carrier substrate consists of a double-side polished substrate with an integrated EL test and Beam-Addressed Release (BAR) ablation layer that improve downstream manufacturing.

In this example, the EPI growth substrate is removed by laser lift-off or chemical means to attach the microLED layer to the carrier substrate with internal test and laser lift-off layers. The carrier assembly is now the microLED production source substrate similar in function to Laser-Induced Forward Transfer (LIFT), a generic materials transfer method originally proposed for materials transfer using scanned laser beams [1].

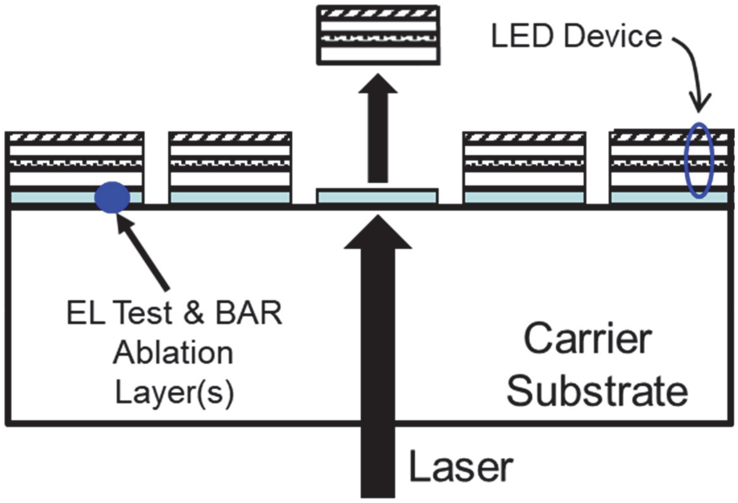

Figure 2: Carrier Source Substrate Example for MicroLED Manufacturing.

This carrier method can be utilized to mount the microLED layer from either a sapphire or silicon EPI substrate. One or more internal layers are integrated before attachment of the detached microLED layer from its EPI growth substrate. Figure 2 includes a release of a microLED by a laser beam impinging on the release layer from the back of the substrate. This structure can allow the individual MicroLEDs to be "printed" or released onto the target display plate or a KGD device bin in a very fast manner using a back-illuminated laser beam addressing method. A binned receptacle of KGD devices could be used by a self-assembly mass-transfer method where only good die is assembled, improving display yield, uniformity and repeatability.

<u>EL Test: MicroLED Known Good Die (KGD) Functional Test</u>

Prior to mass-transfer, KGD testing of the source substrate is necessary to avoid transferring D_{sub} & D_{EPI} defect rates to the overall display yield. This step develops information about the functionality of each microLED and avoids "blind printing" of non-functional devices that would translate to low yield and higher manufacturing cost.

Due to the need for low D_{test} and the sheer number of microLED devices on a source substrate, certain minimum requirements for the test method can be determined. The first is that the test must not misclassify any defect types and increase D_{test} to an unacceptable level. Since the intended function of the devices is electroluminescent (EL), testing using an EL method is desirable. Photoluminescent (PL) testing has been proposed as a proxy for EL testing, but EL defects that nonetheless pass PL test are possible. A microLED device may show good PL response under light excitation but have low EL efficiency at a desired current injection.

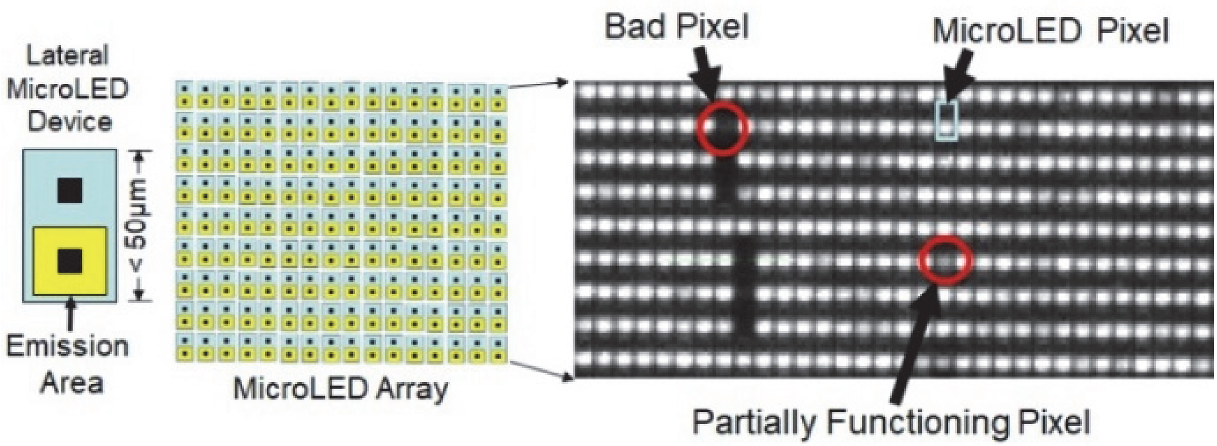

Figure 3: Non-Electrical Contact EL Functional Test of a Lateral MicroLED Device Array.

Figure 3 show a portion of a EL functional test image of a lateral sub-50µm microLED device array using a novel EL test method developed by Tesoro Scientific. The microLED response at different J (A/cm2) is measured as an image of the microLED response utilizing a massively parallel, non-electrical contact method. The data shows the EL response variability and defect levels present that require KGD driven assembly. EL test throughput is production capable (~5' for full 4" wafer test). Although not required, integrated layers can enhance in-process testability.

Figure 4 shows differences between a PL and the corresponding EL image of a portion of the microLED array under test. The PL image shows material response under UV light excitation however the EL test image shows additional defective microLED devices under current injection. The PL response exhibits high D_{test} and thus is not an accurate proxy method to predict microLED EL functional test using current drive.

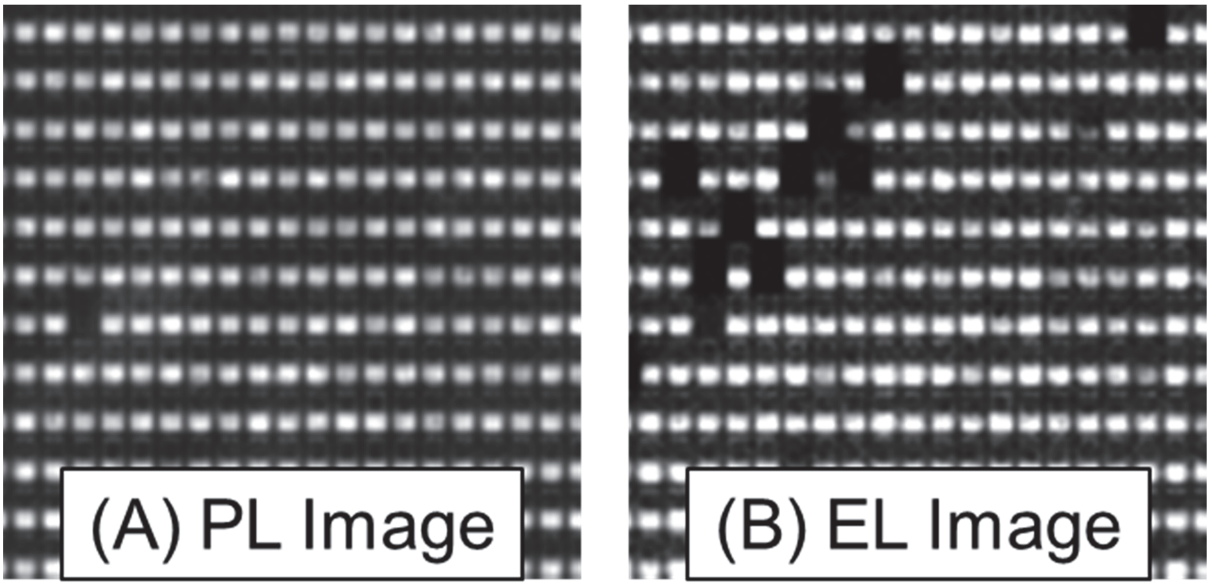

Figure 4: PL (A) & EL Test (B) of a Lateral MicroLED Device Array.

<u>**EL Test Compatible Mass-Transfer Methods**</u>

All mass-transfer methods could utilize the EL test KGD device information, however some are more compatible than others to effect rapid and accurate placement of the microLED device structures from the source substrate. In general, passive pick and place methods are least able to bin and utilize the KGD information without suffering significant loss in throughput. Self-assembly methods would pre-bin the KGD devices to allow assembly of only good devices. "On-The-Fly" methods such as Tesoro's proposed direct laser-assisted assembly method could allow mass-assembly of KGD devices directly without loss of throughput. After the KGD defect file is generated and available, the microLED source substrate and its corresponding KGD file are loaded onto Beam-Addressed Release (BAR) mass-transfer equipment.

The BAR mass-transfer equipment must utilize a KGD data file to avoid transferring LEDs that are non-functional according to preset criteria. The key benefit afforded by this BAR mass-transfer method is its ability to populate KGD LED devices at a high rate estimated to exceed 100-250 million LEDs per hour.

Figure 5 shows a block diagram of a BAR equipment design concept utilizing a tested microLED source substrate (under the scan head) with its corresponding KGD file loaded onto a computer. The scan head would scan the substrate area and quickly release microLED devices according to preset criteria. The population of the microLEDs would then proceed at 50-200k devices per second.

<u>MicroLED Connection to a Target Plate</u>

After mass-transfer, a high-reliability connection method with low D_{cnct} must be employed to complete the electrical circuit. No matter the approach, the connection step would require $D_{cnct} \sim 0$.

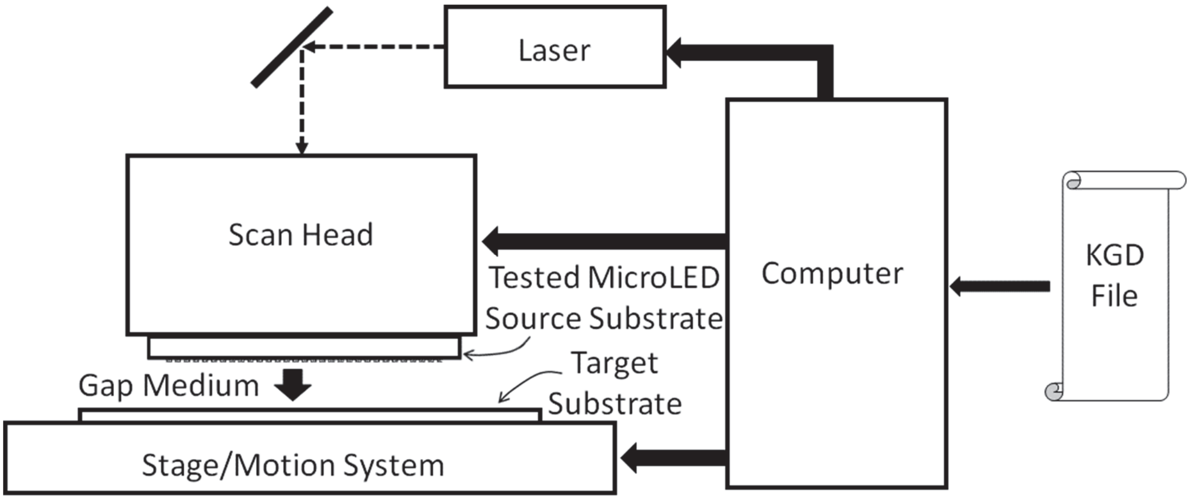

Figure 5: High-Performance BAR Mass-Transfer Equipment Concept.

Conclusion

The key yield and manufacturability challenges of microLED manufacturing were introduced and described. Mass-production compatible in-process test methods are shown to be required for high yield microLED manufacturing.

References

[1] M. Morales & al., "Laser-Induced Forward Transfer Techniques and Applications", Advances in Laser processing (Second Edition), Ed. J. Lawrence, Woodhead Publishing (2017), pages 339-379.