Case Studies in MicroLED End-to-End Process Control

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ABSTRACT

MicroLED displays offer many technical benefits, however, cost remains a barrier to wide market acceptance. Improved yield through process control provides a pathway to high volume manufacturability and lower costs. We discuss end-to-end process control and case studies on release etch for microLEDs and metrology of devices after mass transfer.

1 Introduction

MicroLEDs have many key technical advantages over other forms of display including high brightness, long life, fast refresh, low power consumption, and many more [1]. Beyond conventional display advantages, microLED displays offer the possibility of incorporating sensors, cameras, antennas, drivers, and the like, providing the opportunity for "more than display" interactive functions. Cost, manufacturability, and yield, however, remain key challenges to high volume manufacturing and market acceptance of microLED based displays.

Manufacture of low pixel density or far-eye displays based on mass transfer is significantly different than conventional LCD or OLED paradigms. Assembly of microLED displays involves methods more familiar to micro-electromechanical systems (MEMS) and IC packaging industries. MEMS manufacturing, or heterogeneous micro assembly, involves placement of multiple device types on a substrate, such as red, green, and blue microLEDs, IC drivers, sensors, cameras, antennas, and the like. The challenge is to produce, release, transfer, bond, and verify potentially >100,000,000 devices that are comparable in size to a typical bacterium, but with exacting standards to meet the stringent display yield requirements. Modern LCD and OLED displays meet required yields of >99.9999%, whereas microLED displays will require significant improvements to become competitive.

2 MicroLED End-to-End Process Control

Figure 1 shows a simplified process flow with process control steps, as one representative example of many different potential process integrations [2]. MicroLED production is typically based on sapphire or GaAs wafers but can also be done on Si and other substrates, followed by epitaxial (epi) growth. Both substrate and epi inspection and process control are critical. Subsequent microLED patterning requires inspection and metrology, especially as design rules shrink. The stringent paradigm for microLED process control more resembles Si IC methods than to traditional "good enough" LED process control.

Driver ICs, when used, are based on Si wafers. Their manufacture and process control are well established, as is that for the backplane, however, driver circuitry for microLED is more complex due to the need for pulse width modulation (PWM) driving circuits, as compared to conventional analog refresh circuitry. The possibility of more advanced compensation and direct digital pixel control schemes becomes possible when silicon driver ICs are employed.

Display assembly more resembles advanced packaging than conventional display manufacture such as LCD or OLED. The manufacture comprises the mass transfer and bonding of microLEDs, and potentially driver ICs, sensors, and other elements. Inspection and process control are key to ensure yield entitlement and viable high-volume manufacture (HVM) capability.

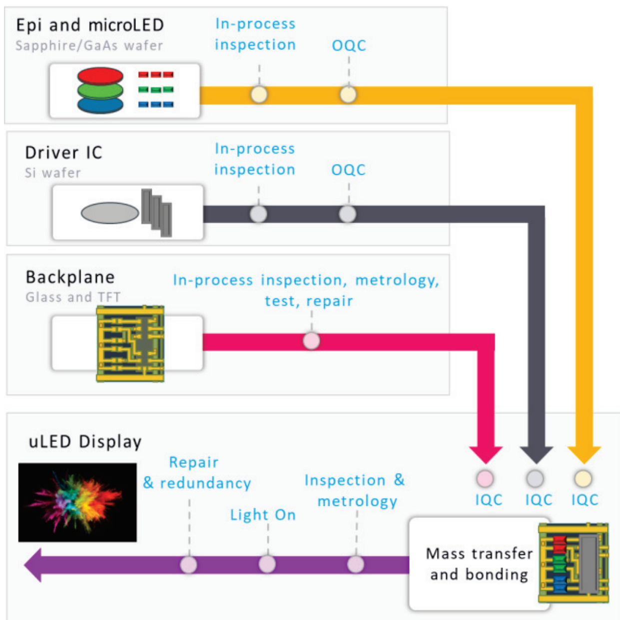

Fig. 1. Representative simplified end-to-end process flow with process control steps for microLED display manufacture.

Net display pixel yield is the product of the individual process yields as illustrated in Figure 2. The yield of the entire process could be significantly impacted by just one step. Best practice metrology, inspection, and process control are required throughout each process step to attain entitlement yield. Even still, to reach 99.9999% yield, an intelligent redundancy and repair strategy is required [3].

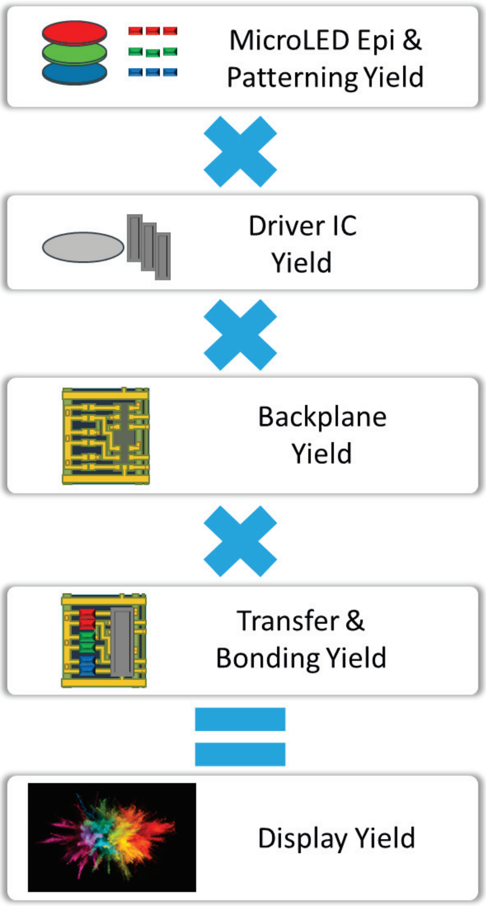

Fig. 2. Net display pixel yield is the combined yield of the individual process yields.

3 Release Etch Processing

This paper will address contact-based mass transfer, such as with a PDMS (polydimethylsiloxane) stamp. Other methods, such as LIFT (Laser Induced Forward Transfer) have different release layer needs. In this case, the release etch and tether structures on the microLEDs involves many process steps, including epitaxy, mesa definition, mirror deposition and patterning, conductor deposition and patterning, etc. Electrodes can be in several configurations including both on top, both on bottom, or both top and bottom depending on the integration. In addition, a sacrificial layer is deposited and patterned. This step is required to enable the release etch process to facilitate transfer-ready devices. Similarly for IC drivers, when used, also require a sacrificial layer and release etch step before mass transfer to the display.

Release etch is well known in the MEMS industry. Typical sacrificial release layers are silicon oxide. Silicon oxide is typically etched by hydrogen fluoride: SiO_2 + 4 HF → SiF_4 (g) + 2 H_2O. Wet etch is the most common method, however, there are issues such as stiction pulling caused by liquid HF and subsequent rinses, as well as corrosion of exposed metals and waste management issues. Dry HF vapor release etch, however, solves all these wet HF etch issues. Dry HF vapor release also has better penetration of smaller features and allows for longer undercuts. The vapor HF/alcohol process[4] further reduces etch residue by ionizing the HF as a catalyst.

The dry vapor HF/alcohol release etch schematic for microLED is shown in Figure 3. A vapor etchant is introduced to remove the sacrificial oxide layer. High selectivity, penetration of small features, long undercuts, minimal residue, no stiction, wide process window and high yield are all critical parameters for a successful process. Supporting tethers are incorporated to hold the devices in place prior to mass transfer. Tether geometries include bottom or side geometries. Electrodes can be on top, or both top and bottom, for example. HF/alcohol low pressure vapor etch release systems includes SPTS Primaxx® uEtch and SPTS Primaxx® Monarch 300, available for both university/laboratory and high-volume manufacturing applications.

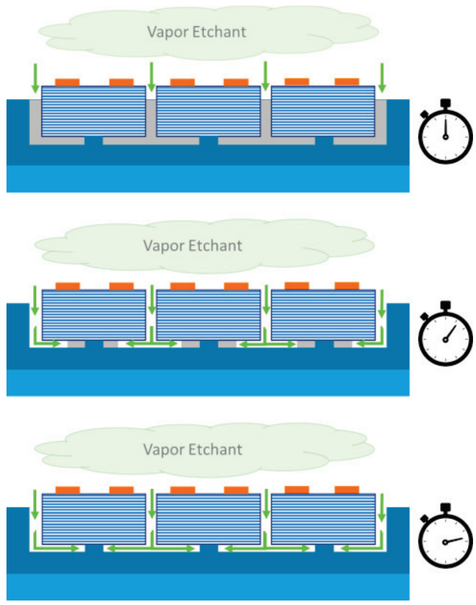

Fig. 3. Dry vapor HF/alcohol release etch of microLED. Vapor etchant is introduced to remove the sacrificial oxide layer (grey). Remaining tether and anchors are shown in dark blue. Electrodes (both on top example) are shown in orange. Substrate is shown in light blue.

4 Mass Transfer Placement Metrology

One or more mass transfer steps are required to move the devices, both microLED and IC drivers, from the tethered transfer-ready substrates to intermediate or final display substrates. There are many approaches to mass transfer (MT). Both high speed and high accuracy are key to successful volume manufacturing and yield. Figure 4 illustrates several key failure modes for which high speed and sensitive metrology and inspection are required. These failure mechanisms include shifts in any direction, device rotation, device deformation, and missing devices. Each of these shifts indicates a reduced likelihood of proper function, whether due to particle interference, incomplete mechanical or electrical bonding, or other similar faults. This fault could be more significant if present on a driver IC, potentially rendering a fully redundant pixel inoperative.

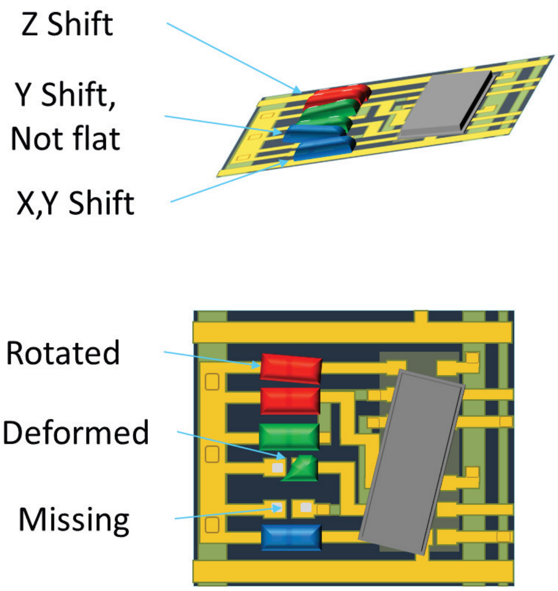

Fig. 4. MicroLED and IC driver shifts in X, Y, and Z, not sitting flat on substrate pads, rotation, deformation, and missing devices are some of the key failure modes that require high-speed and sensitive metrology and inspection, post transfer to the backplane. MicroLEDs are represented in red, green, and blue. Driver IC is indicated in grey

For the example of a PDMS based mass transfer process, stamps of 40 x 40 = 1,600 micro devices are transferred to the receiving substrate. High-speed and accurate shift metrology was performed using the Orbotech Flare™ MT inspection and metrology system. The top row of Figure 5 shows the resulting X and Y shifts in vector map format for an example stamp and for 9 adjacent stamps to the same substrate. Individual device shifts are with respect to printed patterns on the substrate to the center of the device. Shift data can be used in its original form or in statistical aggregation to better inform the manufacturing process.

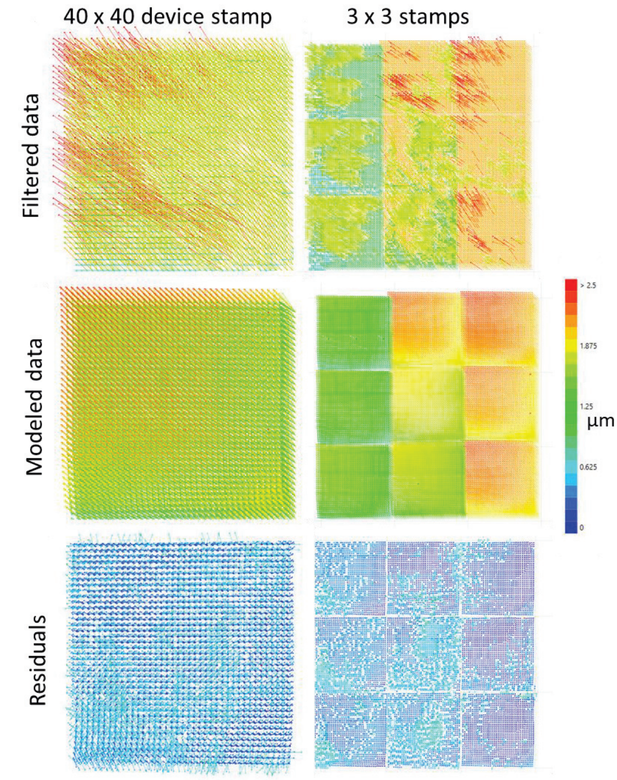

Fig. 5. Shifts in X and Y for a single transfer stamp (left column) and for 9 adjacent stamps on the same substrate (right column). Top row represents data as measured. Middle row is modeled data. Bottom row is residual data. Stamps are 14.4 mm x 14.4 mm. Vectors are color coded by magnitude in microns [5].

Analogous to what is done for lithographic patterning in advanced IC manufacturing, shift data can be modeled to provide improved process control. The middle row of Figure 5 shows polynomial spatial modeled results at both the stamp and panel level. Clear stamp and panel signatures can be identified. Model parameters such as translation, scale, rotation, and higher order effects can also be used for process control. The bottom row of Figure 5 shows model residuals. Model residuals are the delta between the data and the model. They represent the remaining variability that is not included in the model, such as random process noise, random metrology noise and additional minor systematic variations. Note that most of the variability is encompassed by the model for this case.

Shift data, statistical parameters and modeled parameters can be used effectively for mass transfer metrology process control. Feedback use-cases include line and excursion monitor, product disposition, tool calibration, tool qualification, and runtime process correction. Feed forward use-cases can include better informed downstream processing such as binning, stamp selection and scrap, as well as repair and redundancy processing.

5 Conclusions

MicroLED displays have many key technical advantages but manufacturing maturity and higher yield at each step are key to success. Assembly of microLED displays involves methods more familiar to MEMS and IC packaging industries, and experience acquired within these relatively mature technologies is being transferred to microLED display manufacturing. Micromechanical manufacturing, or heterogeneous micro assembly involves placement of multiple device types on a substrate. Release etch, mass transfer and process control are all key micro-mechanical processes for microLED display. Solutions for both release etch and mass transfer process control were presented.

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[5] Mass transfer materials courtesy of X Display Company (XDC), Raleigh, North Carolina, USA.