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Towards Minimizing Customization in Micro-LED Fabrication; A Mass Transfer Process Perspective

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ABSTRACT

We investigate how the requirements for mass transfer techniques influence the fabrication of μ-LEDs. Deterministic mass transfer technologies based on electrostatic and elastomeric stamps and laser-enabled methods are examined along with the recently introduced pattern-sensitive electromagnetic head (PSH) stamp [1].

1. Introduction

The mass transfer process for μ-LEDs may impose a range of constraints on the way the μ-LEDs are designed and fabricated. From a manufacturability perspective, it is desired to minimize the level of customization during μ-LED fabrication. We investigate how the requirements for various mass transfer process techniques influence the fabrication process of μ-LEDs. Focusing on deterministic mass transfer technologies, we review and compare the level of μ-LED customization required to employ the electrostatic and elastomeric stamps and Laser lift off (LLO) against those mandated by the recently proposed pattern-sensitive electromagnetic head (PSH) stamp [1]. Since the electromagnetic nature of the PSH-based mass transfer fundamentally requires the inclusion of thin film magnetic material (e.g. Ni, Sn,...etc) in the metallurgy of the μ-LEDs, we compared the benefits of such shift in metallurgy over that seen on traditional μ-LED contacts today.

2. Customization in M-LED Process Flow

While examining the various levels of customization required by the considered mass transfer techniques, we identify two key common requirements for the elastomeric, electrostatic and laser techniques. These are (1) planar μ-LED s and (2) the use of carrier wafer, where the epi wafer is bonded onto an intermediate wafer carrier. Whenever a carrier wafer is employed, the concerns for die stabilization and release become evident. In addition, there are specific requirements associated with each method which will be addressed individually.

2.1 Elastomeric Stamp

The elastomeric technique employs a PDMS stamp which relies on Van Der Walls force to hold the μ-LED die. The pickup and release actions depend on both the material characteristics of both the device to be picked and the speed at which the stamp approaches the device [2]. A sacrificial, lattice-matched thin release layer on which the epi layers are grown is a key requirement. This sacrificial layer is subsequently removed from underneath the devices, leaving them attached to the native substrate by micro-fabricated structures (tethers), as illustrated in Fig.1. The tethers are meant to fracture during the pick-up step of the transfer process. The tether mandate results in wasted epi real estate, requiring minimum "street" width between divices of about 6 μm in one direction and 3μm along the other direction [3].

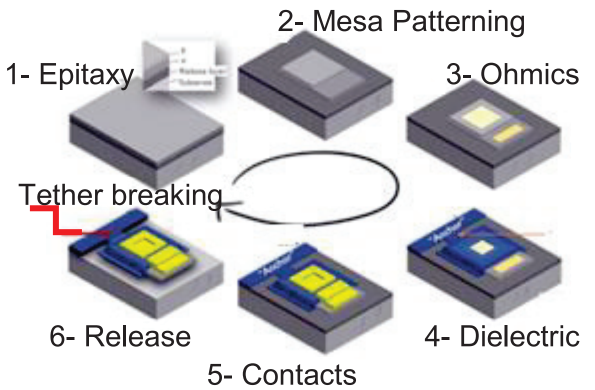

Fig. 1: Custom process flow for the fabrication of μ-LEDs for elastomeric mass transfer method [3].

Since the technique depends on the fracture of these tethers, defect performance and need for PDMS stamp cleaning become real manufacturing concerns. In addition, the technque requires a "perfectly" flat μ-LED substrate, which may suggest its intolerance to normal variabilities during μ-LED manufacturing [3].

2.2 Electrostatic MEMS

Bibl et al. developed an electrostatic stationary transfer head, which then evolved into a set of compliant MEMS, employing voltage-induced adhesion force to transfer the μ-LEDs [4]. However, this transfer method is sensitive to the air gap, usually present due to the normal variabilities in the μ-LED fabrication process, between the μ-LED and the transfer head. Increasing the applied voltage to overcome the airgap might cause μ-LED breakdown. The process flow associated with the fabrication and transfer of the μ-LEDs is schematically shown in Fig. 2. Note the use of carrier wafer and laser lift off to detach the epi layer from the sapphire substrate. Here both the carrier and epi wafers go through the patterning process. Critical alignment is required between the pattern generated by the reflective layer on the epi wafer and that which defines the stabilizing posts, on the carrier wafer, for the yet to be formed μ-LEDs.

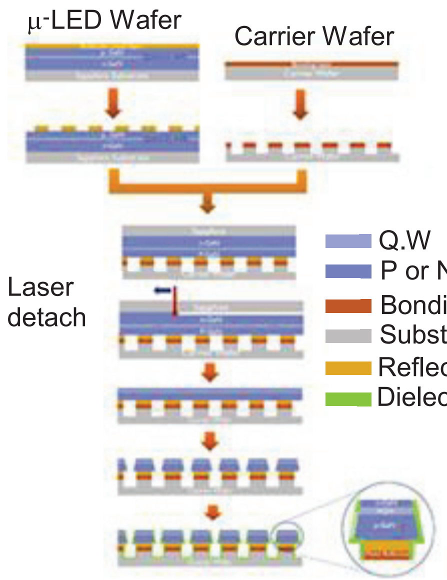

Fig. 2: Process flow for the fabrication of μ-LEDs as mandated by the electrostatic mass transfer method [3].

2.3 Massive Parallel Laser Enabled Transfer (MPLET)

Marinov introduced a mass transfer technique for μ-LEDs from the source epi-wafer to a quartz carrier [5]. From there, the μ-LEDs are selectively transferred to the display panel using massively parallel laser-enabled transfer (MPLET). Figure 3 capture the various steps and requirements of the transfer process. The technique relies on a sacrificial layer (dynamic release layer, DRL) that will be later removed under laser illumination to release the μ-LEDs.

2.4 Electromagnetic Pattern-Sensitive Head (PSH)

A stationary stamp containing an array of high magnetic permeability (high mu) material in which micron-scale discontinuity were introduced corresponding to the layout of the μ-LEDs to be transferred [1]. When placed in a switchable magnetic field in a direction parallel to the substrate, magnetic flux lines leave the high mu material at each discontinuity, couples to the thin magnetic material in the contacts of the μ-LEDs, generating a magnetic force to pick the specific μ-LED, as demonstrated on Fig. 4. The technique, which does not employ any carrier wafers, is equally suitable for epi substrates grown on either sapphire or Si substrates. Figure 5 illustrates the entire PSH-based transfer process flow. It is a fundamental requirement that the μ-LEDs contain magnetic material. Although this requirement may be viewed as a constraint, it represents the least customization effort during μLED fabrication, as discussed in the Sec. 3.

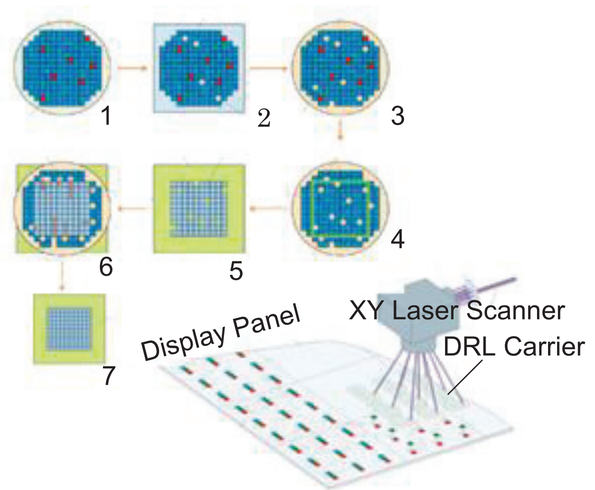

Fig. 3: Process flow for the fabrication of μ-LEDs as mandated by the Laser Enabled Transfer [5]. Steps 1-3 represents wafer-to-DRL carrier transfer while steps 4-7 are for DRL carrier-to-panel transfer. "Red" dots represent bad dies which should be replaced before the laser transfer step.

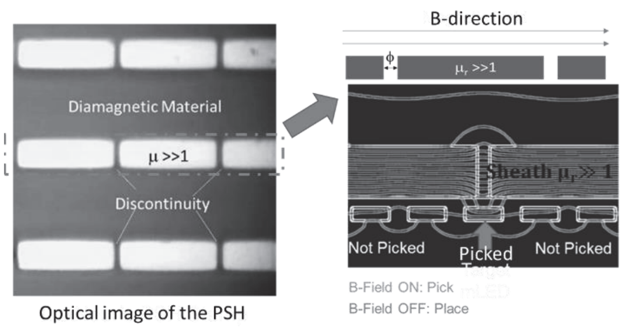

Fig. 4: Optical image of the PSH (left) and an illustration to principle of operation (right). Note magnetic flux lines are mainly "confined" to the continuous high μ-sheath metal.

During the bulk transfer phase, the PSH discontinuities pattern matches that of the μ-LEDs on the native epi wafer. The transfer process employs intermediate reusable tray on which all dies are transferred from native substrate. Using a single die PSH mounted on a fast pick & place machine, scattered bad dies are replaced yielding an assembly of all known-good-die (KGD) on the tray. The selective phase of the transfer picks dies from the KGD tray to the pixel assembly tray or the display panel directly. The selective PSH head has

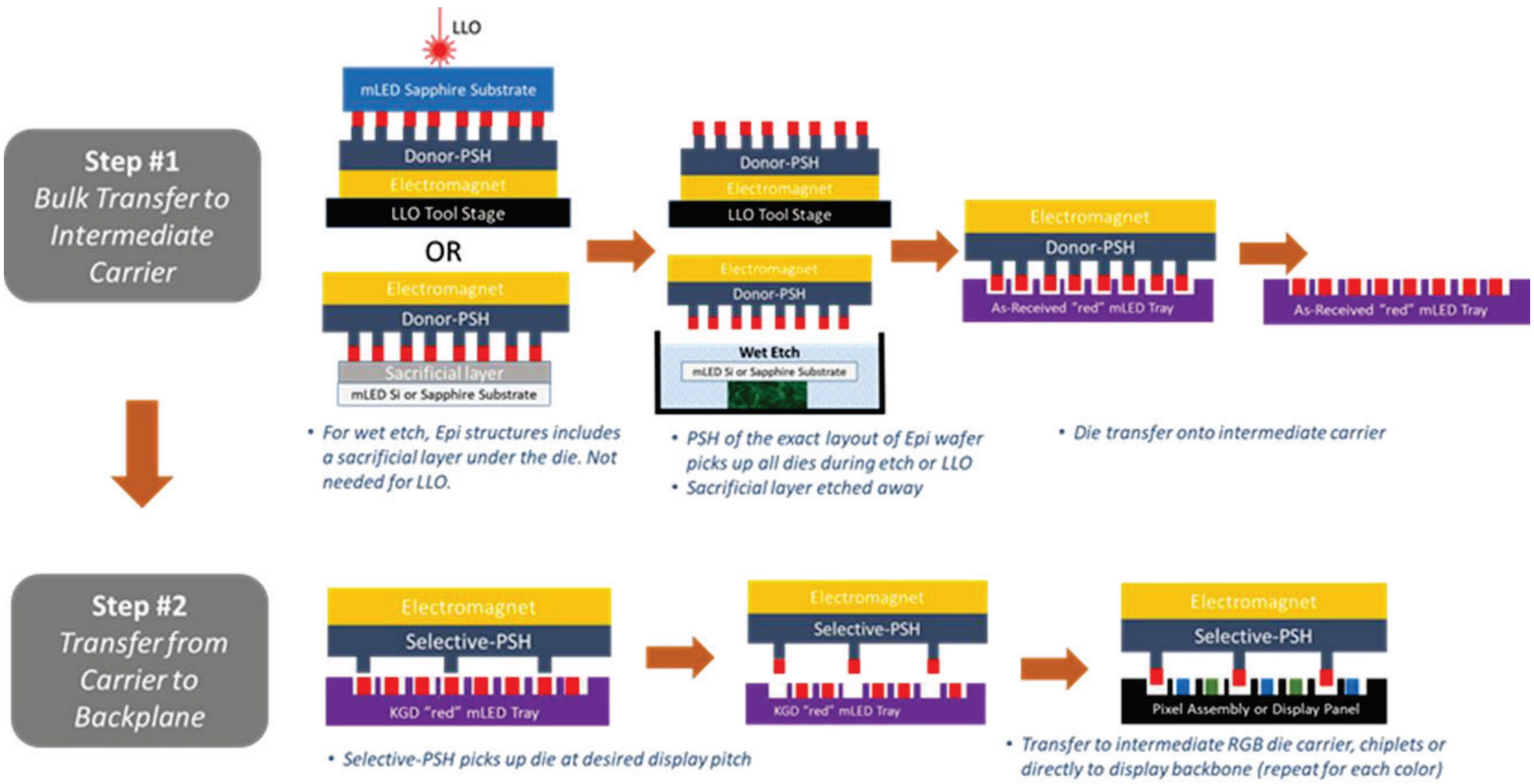

Figure 5: Schematics of the two-stage transfer process employing the PSH method.

the same exact discontinuity layout as the receiving substrate. Due to the scalability of the PSH itself, the stamp can be fabricated to accommodate small to large substrates. The PSH may be fabricated on glass, silicon or even non-magnetic metal substrates, using known thin film deposition techniques.

3. Contact Metallurgy

When a metal is brought into intimate contact with a semiconductor (the p- and n- sides of a μ-LED), the valence and conduction bands of the semiconductor are brought into a definite energy relationship with the fermi level in the metal. The purpose of the contacts is to deliver power to the P and N wells. These contacts need to have low electrical resistance and meet the requirements for thermal, mechanical and reliability performance metrics. Traditionally, gold, silver, chrome and tin compounds are common solder metals in the LED industry. We note here that chrome and tin are soft magnetic materials. However, advancements in lead-free solder metallurgy fueled by advanced microprocessors demand for more I/O bandwidth, coupled with the drive for μ-LEDs scale down to the few micron size, other contact elements and/or compounds containing nickel, copper and other less expensive metallurgy than gold and silver, are expected to be used in the very near future. For example, flip-chip InGaN μ-LED was fabricated using a similar process to that for flip-chip broad-area LEDs, but with scaled device size and ITO, Ni or Ni/Au layer deposition as transparent contacts for p side [5]. For the PSH-based mass transfer, the magnetic material may be either part of the contact metallurgy itself, as in the example above, or deposited as an added layer on the contacts. In this case, the metal-semiconductor interface is independently optimized without the constraint of having the magnetic material. Compared to the use of carrier wafer option and/or the detailed process flow and specialized material used in alternative mass transfer methods, the manufacturability prospective of the PSH-based method is encouraging.

4. Discussion

Mass transfer, like all other key processes in the fabrication flow of μ-LED display must be production-worthy. The manufacturability requirements include, but not limited to, minimal customization of the μ-LED fabrication process, tolerance of the mass transfer technique to variabilities in μ-LED fabrication, low defect performance, low fabrication cost for the transfer stamp itself, and low cost transfer process. Fundamentally, both the elastomeric and electrostatic transfer methods require high level of μ-LED planarity beyond the expected +/- 10% (3σ, 3 standard deviations). On the other hand, μ-LEDs transferred using the MPLET may be susceptible to damage from the laser. Additional defect performance concerns are raised with the elastomeric method due to the breakage of the tethers and with the electrostatic method due to the potential damage to the μ-LED from increasing the grip voltage required to compensate for μ-LED height variations [4].

5. Conclusions

Examining the PSH-based mass transfer reveals the least level of μ-LED customization while provides the highest level of manufacturability. The inclusion of magnetic material in the μ-LED contact metallurgy may be already present. In any case, adding thin (1-3 microns) of Ni, Sn, Cr or any other magnetic material on top of the standard contacts, if used, meets the electromagnetic PSH-based transfer requirement.

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