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An Alternative Micro LED Mass Transfer Technology: Self-Assembly

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***Abstract*—Micro LED display technology has been spotlighted as the most promising technology compared to LCD and OLED. Its excellent advantages include higher brightness, self-illumination, higher resolution, lower power consumption, faster response, higher integration, higher stability, thinner thickness, longer life, etc. In terms of the unique benefits, it is attracting increasing attention from industries. With the commercialization of Micro LED technology, the following hurdles are identified: wafer manufacturing, full color, bonding, and mass transfer. Among them, mass transfer is so far considered as the most severe bottleneck. Several mass transfer technologies have emerged, including fine picking and placing, roll printing, laser transferring, and fluid self-assembly, which aim to solve the mass transfer problems. However, the aforementioned first 3 types of technologies still rely on the pick-and-place process, which is limited when the Micro LED die dimension shrinks to smaller scales due to processability and equipment precision. Fluidity self-assembly, on the other hand, will not be constrained by the Micro LED size and machine accuracy in the mass transfer process, which received increasing attention from researchers. In the self-assembly of component level, gravitational attraction, magnetic /electromagnetic fields, and capillary force are considered the mainstream force to facilitate the assembly process. Therefore, the component self-assembly becomes a prospective substitute for the Micro LED mass transfer solution, which overcomes the problems of the trade-off between throughput and the placement accuracy of the pick-and-place technology.**

Keywords—Micro LED, Mass transfer, Pick-and-place, Self-assembly

I. INTRODUCTION

With the rapid development of the electronic industry, displays serve as a medium to present digital information, which is attracting increasing attention from the academy and industry. Generally, liquid crystal display (LCD) and organic light-emitting diode display (OLED) are two dominant display technologies in modern life. However, both of them still face shortcomings limiting their further application[1]. LCD's major challenges are limited contrast ratio and flexibility. On the other hand, OLED has two shortcomings to overcome: the compromise between lifetime and luminance, and relatively high cost[2]. Recently, the Micro-LED display has come into the spotlight. Micro LED, based on gallium nitride (GaN) based LEDs, also known as an LED with a typical size between 1μm and 100 μm, without sapphire substrate[1, 3]. Dawson and Satoshi have pioneered the development of Micro LED arrays for applications of displays, VLC, etc[4, 5]. Micro LED display technology is attracting extensive attention from academic scholars and industrial researchers. Its excellent advantages include higher brightness, self-illumination, higher resolution, lower power consumption, faster response, higher integration, higher stability, thinner thickness, longer life, etc[3].

With the commercialization of Micro LED technology, the following hurdles are identified: wafer manufacturing, full color, bonding, and mass transfer[6]. Among them, mass transfer is so far considered the most severe bottleneck, which requires tens of millions of Micro LED dies to be placed at the pattern of the target substrate precisely (ideally ppm level misalignment) and rapidly (millions of dies per hour) to form reliable electrical connections and mechanical support[1, 6]. The conventional method of assembling Micro LED dies through picking-and-placing one by one may take months, whose inherent defects cause low yield, low efficiency, and ultra-high cost. In facing this serious problem, many researchers proposed different solutions, including fine picking and placing, roll printing, laser transferring, and fluid self-assembly. For fine-picking-and-placing, LuxVue, which Apple acquired, utilized an electrostatic transfer head generating the electrostatic attraction and repulsive force, further realizing the picking-up and placing of a Micro LED array, respectively[7]. X-Celeprint proposed a solution, that sticks Micro-LED arrays through a soft elastomeric stamp, releasing the dies onto patterns subsequently[8, 9]. A programmable magnetic module was applied by Industrial Technology Research Institute (ITRI) to pick and place die via electro-magnetic force, whereas magnetic ingredients like iron, cobalt, and/or nickel should be inserted into Micro LED dies[10]. Korea Institute of Machinery and Materials (KIMM), employed a method of roll printing, Micro LED dies can be printed onto the patterned substrate from a roller's carrier tape, which has pre-transferred Micro-LED arrays[11, 12]. Laser-assisted transferring was studied by Uniqarta, which was acquired by Kulicake and Soffa (K&S), utilizing the laser-generated ablation on a sacrificial layer to release Micro LED dies from the tape[13].

Although the aforementioned former three mass transfer approaches can significantly improve transfer efficiency, they don't eliminate the action of picking and placing. There is no doubt that those methods will be constrained when the Micro LED die dimension shrinks to smaller scales due to processability and equipment precision. However, fluidity self-assembly will not be constrained by the Micro LED size and machine accuracy in the mass transfer process.

II. SELF-ASSEMBLY TECHNOLOGY

Self-assembly refers to the self-organization of components into ordered structures without human intervention, whose processes are common in nature. The technology can be applied to a wide range from the molecular level to the component level[14, 15]. The examples are depicted in Fig. 1. Molecular self-assembly is mainly driven by hydrophobic interaction, van der Waals, electrostatic, coordination bond, and hydrogen bond to form nano/micro-structure. In the self-assembly of component level, gravitational attraction, magnetic/electromagnetic fields, electric fields, and capillary force are considered the mainstream force to facilitate the assembly process[15]. Therefore, the component self-assembly could be a promising candidate for the Micro LED mass transfer solution, which can overcome the problems of the compromise between throughput and placement precision of pick-and-place technology.

In this paper, recent technological developments of component self-assembly were reviewed from the aspect of driving force, to evaluate the achievability of the technology for Micro LED mass transfer research.

III. COMPONENT LEVEL SELF-ASSEMBLY TRANSFER

Self-assembly occurs in the fluid phase or on smooth surfaces to keep the component mobile[14]. The external force is implemented to facilitate the self-assembly process. Table 2 shows a synoptic summary of the general methods of component level self-assembly hereby reviewed.

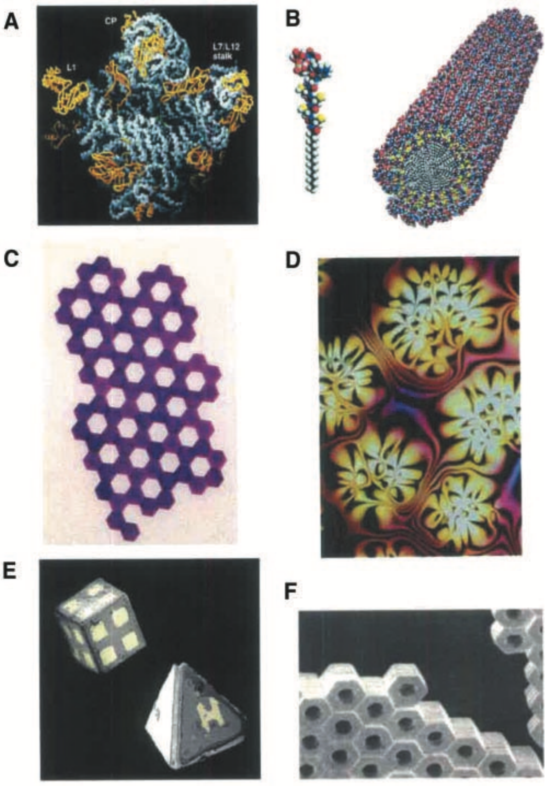

Fig. 1. Example of self-assembly on various scales[14].

TABLE I. A SYNOPTIC SUMMARY OF COMPONENT SELF-ASSEMBLY TECHNIQUES

Driven force	Benefits	Limitations
Gravitational attraction (shape matching)	Components can be recycled	Manipulating complexity for components and substrate Unfavorable gravitational attraction downscaling
Magnetic/electro-magnetic fields	Non-contact forces Components can be recycled	Complexity for IC manipulating Further processing for magnetic layer and/or transfer
Electric fields	Non-contact forces Favorable force downscaling	Need further processing for electrical connections and mechanical support
Capillary force	Self-alignment Programmable and multi-batch	Process-sensitive caused by weak non-polar contact Self-alignment Effects on joint reliability

A. *Gravitational attraction*

Generally, the gravitationally attracted self-assembly requires shape matching for donors and acceptors. Yeh and Smith pioneered the research on the self-assembly of GaAs chips on silicon substrates through gravitationally attracted self-assembly (Fig.2), in which, fluid transport and shape matching for placement and orientation were utilized to perform the excellent transferring. The truncated trapezoidal pyramids shape was designed and manipulated for the devices, which fit inside etched-hole receptors on the substrate. After self-assembled, the substrate was taken out from the liquid, dried, and further bonded for electrical interconnections. However, only around 90% yield was achieved. What's worse, the yield is further reduced to 30-70% after liquid evaporation due to the surface tension[16]. Inspired by the shape matching concept, representative company-eLux re-designed the structure of LED dies and holes on the substrate. As depicted in Fig. 3, on top of the die, a metal pillar was fabricated, they demonstrated the transfer process by utilizing a carrier liquid to transfer Micro LED dies onto the target substrate and assembling them in position for each pixel. In which, the metal pillar helps the die rotate if misaligned, to guarantee the die and hole are in the correct position. Importantly, more Micro LED dies than required for the number of pixels in the transfer process, and the left-over dies and carrier liquid can be recycled. The yield can reach as high as over 99.9%[17]. Nevertheless, the metal pillar needs to be removed after assembly is completed. Otherwise, the functionality of the LED devices might be affected. Manipulating the metal pillar onto the top of the die and removing it brings technical obstacles and potential risks.

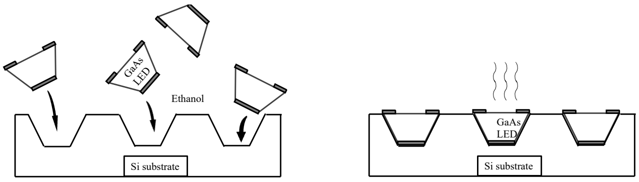

Fig.2. The schematic diagram of gravitational attracted self-assembly Micro-LED mass transfer with truncated trapezoidal pyramids shape matching[16].

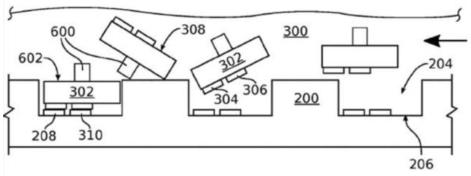

Fig.3. The schematic diagram of gravitational attracted self-assembly Micro-LED mass transfer with metal pillar matching[17].

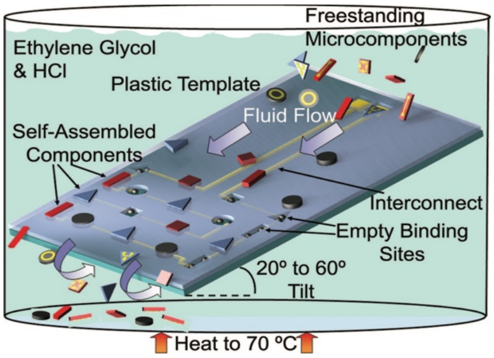

Fig.4. The schematic diagram of the heterogeneous self-assembly process with shape matching[18].

The self-assembly of silicon devices on a flexible substrate was reported by Stauth and Parviz. As depicted in Fig.4, complementary shapes (including circular, triangular, and rectangular) recognition was applied to assemble multiple micro-component types selectively in the fluidic medium. Furtherly, the soldering process (low-temperature alloy) was performed to form the electrical and mechanical connection between components and substrate. Finally, a 97% yield was realized for substrate, which contains 10 000 binding sites within 25 mins[18]. In the real world, selective self-assembly through multiple shapes will be a challenge for die fabrication and/or component packaging, solder joint reliability issues also limit the end application, since the low-temperature alloy is used in this case.

B. *Magnetic/electromagnetic fields*

Magnetic forces have been applied as driven forces for component-level self-assembly. Benefits from the attraction and repulsion of magnetic polarization, which can be adjusted by material, magnet geometry, and magnetization direction as well. In 2008, magnetically-induced self-assembly of 1 mm*1 mm* 0.5 mm silicon devices into a regular pattern on a target substrate without any other guiding template was reported by Shetye et. al.[19] The permanent SmCo magnets were embedded, and microfabricated into components, which were self-assembled into the corresponding binding sites of the target substrate. The components were placed in a container connecting with a micromechanical shaker, above the base of the container, and the target substrate was placed at a distance of 10 mm. The number of components used is approximately 5 times the number of acceptor sites, the components bounced up and down and self-assembled onto the substrate with the vibration of the shaker. However, stacking and misalignments issues were observed, the former might be caused by the excessive magnetic attraction, the latter attributed to the shape of magnets of the fairly axisymmetric square. They claimed that with additional vibration, those two issues can be alleviated. Although rapid and precise assembly is achieved, the introduction of magnetic elements brought difficulties to component fabrication and might affect the assembled devices' performance. Selfarray, an American start-up company, demonstrated its magnetic-oriented self-assembly technique, as shown in Fig.5. LED die was pretreated with a thin ferromagnetic layer bonded to a pyrolytic graphite layer on the outer surface. At the same time, prepared a magnetic platform comprising a plurality of magnets arranged in an array. In the assembly process, LED dies can be quickly assembled to the target position under the action of the magnetic field, and then transfer to the target substrate through intermediate media such as polydimethylsiloxane (PDMS) film. After assembly was completed, removed the diamagnetic layer from the LED die to guarantee the following bonding between die and substrate[20]. In essence, this is the pre-arrangement of components and needs to be transferred to the substrate. The technology challenges in the transfer process and the adaptability to smaller LED die remain to be discussed.

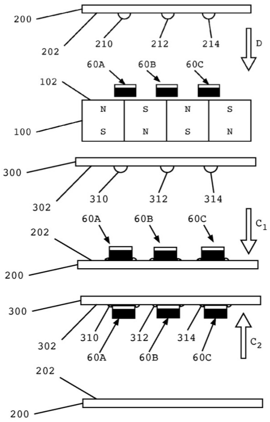

Fig.5. The schematic diagram of magnetic driven self-assembly Micro-LED mass transfer[20].

C. *Electric fields*

The application of electric fields in self-assembly may provide a non-contact handling approach, which can be manufactured by trapping electrodes in a massively parallel way. O'Riordan et al. reported a programmable electric field method that drives the field-assisted self-assembly of mesoscale objects and devices[21]. The GaAs-based LED dies, which have a size of 50μm diameter, could be moved across the electrodes and assembled onto selected receptor electrodes by switching field configurations. After assembled, the transport medium was evaporated, and further, go through the soldering process to form solder joints between devices and substrate. Dielectrophoresis (DEP) can affect both charged and uncharged bodies at the same time, possibly be a more compelling approach to achieving micro-device self-assembly successfully. Lee and Bashir's group used dielectrophoresis and chemical molecules to implement the three-terminal single-crystal silicon devices self-assembling onto the target receptor (Fig.6)[22]. In this study, a substrate with 1,9-nonanedithiol coated electrodes and a solution containing the devices were prepared in advance. An alternating electric field was applied between two electrodes, to facilitate capturing the devices which present positive DEP due to the metal contact. The contact resistance between devices and substrate electrodes was reduced through a subsequent thermal annealing process.

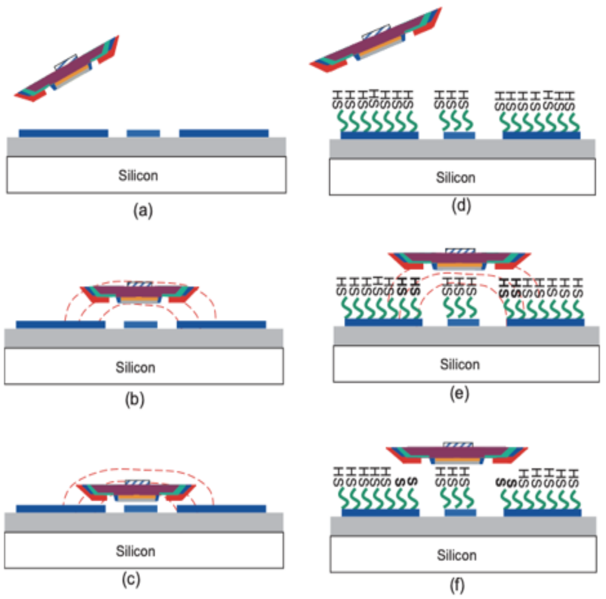

Fig.6. The schematic diagram of electric fields driven self-assembly transfer. a-c) DEP-mediated assembly, and d-f) DEP and chemically mediated assembly[22].

D. *Capillary force*

In capillary force driving self-assembly, liquid or molten solder is used as the medium between the connecting device and the target receptor. The surface energy tends to be minimized to drive the micro-device to bind to the target site. Srinivasan et al. described fluidic capillary-driven self-assembly of micro silicon components onto target locations of silicon and/or quartz substrates as shown in Fig.7[23]. The patterned substrate was passed through a film of hydrophobic adhesive on water, and the layer of adhesive was coated on the binding sites selectively. Next, the microscopic parts were toward the substrate surface underwater utilizing a pipette directly. When the hydrophobic coated components contacted with a hydrophobic adhesive-modified substrate receptor binding site, shape matching occurred simultaneously to minimize interfacial free energy. After that, the permanent bonding joint was formed by the polymerization of the adhesive. In this approach, the negative effect of gravity of parts can't be avoided, which might bring the extremely high technological requirement during assembly, otherwise, the final yield might be affected significantly. Seongkyu et al. reported a fluidic self-assembly process exploring low-temperature melting solder alloy to assemble GaN microchips. As depicted in Fig.8, the template was patterned with Au pads and a dip soldering process was implemented to leave molten solder (melting point: 60 °C) on those Au pads area in an acidic environment to avoid solder surface oxidation. 3 million GaN dies with a circular shape and tin alloy coated substrate was put in a glass vial, in which, the solution of 2 wt% surfactants and a few amounts of hydrochloric acid (HCl) in deionized water was filled. The vial was heated above the melting point of the alloy, the chips were rotated inside, then attracted, aligned, and further bonded with the target template due to capillary force. The final yield can be achieved by 99.9%. This low-cost and simple assembly method shows great potential for Micro LED mass transfer technology. However, this technology is immature yet and still needs deep development since the low melting point alloy limits commercial usage on reliability issues.

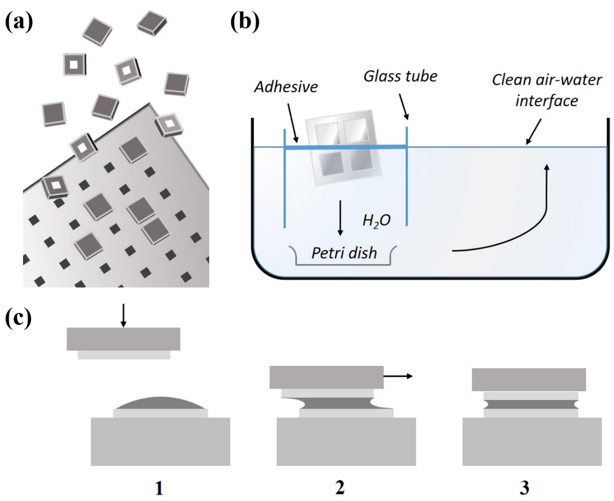

Fig. 7. The schematic diagram of (a)liquid capillary force driven self-assembly technique, (b) substrate adhesive-coating procedure, (c) self-assembly using capillary forces of the adhesive[23].

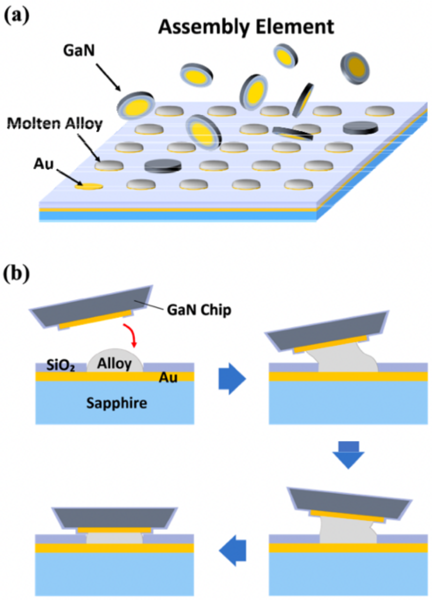

Fig. 8. The schematic diagram of (a) assembly elements, and (b) molten solder capillary force-driven self-assembly Micro-LED mass transfer[24].

IV. CONCLUSION

In conclusion, with the further commercialization of Micro LED display technology, the conventional assembly process of pick-and-place does not fit the demand for processing such small Micro LED dies rapidly and precisely. Therefore, novel Micro LED mass transfer technologies including fine picking and placing, roll printing, and laser transferring were raised. However, these techniques face the issue of a compromise between throughput and placement precision since still rely on picking and placing. Self-assembly emerges as a promising assembly alternative, which is not constrained by the shrinkage of Micro LED die dimensions. A diverse set of driving forces for the self-assembly processes were reviewed. Although attractive results have been achieved, further explorations and optimizations are still needed to facilitate industrial adoption. With further evolution of the Micro LED mass transfer self-assembly technology, a bright future of more accessible, faster, and more precise assembly technology will be present.

This will greatly accelerate the commercialization of Micro LED displays.

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