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ABSTRACT

Micro light-emitting diode (Micro-LED) is a highly promising technology in the field of new displays, with the mass transfer process involved in its manufacturing process widely regarded as a major barrier to their further development. This study adopts laser transfer technology as the primary solution, using ablation-type transfer release materials that improve chip utilization rates over blister-type release materials. In addition, measurement of the laser transfer parameters, inspection, and laser repair technology are combined to achieve a transfer yield of about 100% to the carrier substrate and a cumulative transfer displacement of less than 1 μm in the Micro-LED inverted chip array. Furthermore, cleaning agents were used to remove adhesive residue from the receiving substrate after transfer, improving the bonding yield between the chip and the thin film transistor driver circuit board. This study provides a feasible solution for Micro-LED mass transfer, which could boost its further development toward commercial application.

I. INTRODUCTION

Modern display technology focuses on Micro light-emitting diode (Micro-LED) with 1–50 μm mesa sizes for its exceptional performance. Micro-LED has better brightness, lower power consumption, longer lifespan, millisecond response time, larger RGB color gamut, and other advantages over standard organic light-emitting diode (OLED)[1–3] and liquid crystal display (LCD)[4–6] technologies. It is considered a crucial technological advancement following LCDs and OLEDs.[7] So far, Micro-LEDs have shown extensive application potential in areas such as augmented reality (AR)/virtual reality (VR) display,[8] high-definition televisions,[9] projectors,[10] smart devices,[11] etc.[12]

Micro-LED commercialization faces technological obstacles and high production expenses despite its potential for various applications.[11–14] The mass transfer process requires transferring a large number of Micro-LED chips from the native substrate to the target substrate, making it difficult to achieve high yield, high precision, and high efficiency. Mass transfer is a crucial step in Micro-LED manufacturing and one of the biggest obstacles limiting their further development. The mass transfer includes accurately and efficiently releasing millions or tens of millions of Micro-LED chips from the native substrate and parallel transfer to the target substrate.[14] This process needs complex transfer and bonding methods. To address the challenges of mass transfer in the fabrication of Micro-LEDs, diverse methods have been proposed,[11] such as electrostatic transfer,[15] stamp transfer,[16,17] fluid self-assembly transfer,[18] roll-to-roll transfer,[19] and laser transfer.[20–23] The electrostatic transfer is precise but costly and can damage LED chips; stamp transfer is low-cost but inefficient for large-area high-density arrays; and fluid self-assembly transfer offers high precision, but its control is complex, and selectivity is poor and has a low yield. Roll-to-roll transfer favors large-scale production but has lower precision. These methods' shortcomings normally include low efficiency, high cost, and unsatisfactory placement precision.[24–26] By contrast, laser transfer technology offers notable advantages in addressing these issues. Its specific benefits are given in the following. (1) Controlling the laser parameters allows high position precision and low chip damage from mass transfer.[20] (2) The laser transfer process minimizes physical contact, thereby minimizing mechanical stress and chip or thin film damage, which is appropriate for situations requiring high efficiency.[20] (3) By tailoring the laser spot size, laser transfer can typically remove defective chips and repair missing chips quickly, resulting in higher transfer yields.[20] (4) With programmable laser transfer, the Micro-LEDs can be redistributed at a set pitch in a different layout from the original wafer. With its high selectivity and reliability, this method shows promising prospects for industrial production.[20,27–29]

During the laser transfer process, Micro-LED chips on a sapphire substrate are typically separated and transferred first to a temporary substrate called carrier 1. Inverted chip arrays are then transferred from carrier 1 to carrier 2 and finally bonded carrier 2 to the thin film transistor (TFT) driver circuit board to achieve light emission. A laser beam passes through a transparent substrate and acts upon the laser-sensitive layer material, causing photothermal or photochemical reactions at the interface, which allow the microdevices to overcome adhesion forces and transfer to the target substrate.[30,31] Regarding the different materials used in the laser-sensitive layers, one may apply different laser transfer modes, which can cause different interface phenomena. The modes typically can be classified into two kinds. (1) Direct decomposition: the laser-sensitive layer material is ablative, absorbing laser energy at the interface to react and decompose, and generating gas thrust to weaken the adhesion force between the device and interface. This mode is excellent in principle, but until now there is little report regarding its application in Micro-LED's mass transfer, probably because of the difficulty in finding an appropriate material that fulfills all the stringent requirements.[24] (2) Indirect decomposition: the laser-sensitive layer material is blister-type material, being abraded to a certain depth at the interface and creating gas bubbles that result in the device detaching from the laser-sensitive layer and transferring to the receiving substrate.[24,32] Due to the close distance between native chips, however, bubbles produced by blister-type materials may affect adjacent chips during laser irradiation. As a result, displacement occurs in four adjacent chips of each chip in the transferring process, rendering three-quarters of the chips in the original chip array useless.[30] Nevertheless, Micro-LED display manufacturing in practical industrial applications places high demands on precision and defect-free production. Accordingly, the industry requires a transfer process that not only offers excellent yield and precision but also the ability to detect and repair damaged pixels after transfer.[24,27]

In this work, we will demonstrate the successful transfer of Micro-LED chips with a size of 15 × 30 μm^2 using laser transfer technology, achieving a single-shot transfer quantity of 6400. As opposed to the traditional approach, here we have carefully selected an ablative material instead of the blister material and used it to maximize the utilization rate of the Micro-LED chips, avoiding the chips being lost or displaced by the bubbles. With the combination of laser parameter optimization, inspection, and laser repair, this study has achieved a replacement of defective chips with intact ones and finally attained a 100% transfer yield to carrier 2 and cumulative displacement of less than 1 μm for the Micro-LED inverted chip array. As compared to prior research, this study provides a significantly superior transfer yield and precision. Finally, a Micro-LED display was successfully fabricated by bonding the chip array to the TFT driver circuit board. This research offers a viable solution for the mass transfer of Micro-LEDs, potentially driving their further development toward commercial applications.

II. EXPERIMENTAL SECTION

Figure 1 shows the entire process of the experiment. The Micro-LED chips are bonded to a temporary substrate using a 4-inch quartz glass wafer called carrier 1 and spin-coated with an adhesive layer [Fig. 1(a)]. The sapphire substrate is then taken off by laser-lift-off (LLO) [Fig. 1(b)]. As a result, the Micro-LED arrays are released to carrier 1 [Fig. 1(c)]. After the LLO, Micro-LED chips are transferred to another substrate called carrier 2, a 30 × 30 mm^2 ITO glass, by using laser transfer technology [Fig. 1(d)]. The Micro-LED chips are

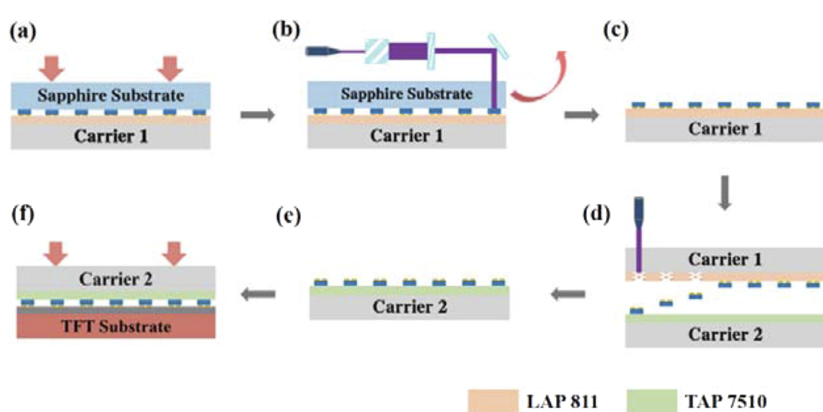

FIG. 1. Working procedure of this experiment. The steps include (a) bonding the Micro-LED chips to carrier 1, (b) conducting the LLO, (c) removing the sapphire substrate, (d) transferring the Micro-LED array to carrier 2 by laser transfer, and (e) and (f) flip-chip bonding to the TFT driver circuit board.

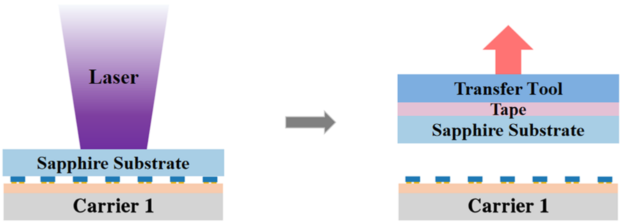

FIG. 2. Steps of the LLO process.

turned upside down [Fig. 1(e)], particularly suited for the flip-chip bonding to the TFT driver circuit board [Fig. 1(f)].

A. Temporary bonding

The prepared carrier 1 was ultrasonically cleaned for 10 min with acetone and isopropanol, followed by a deionized water rinse after each step to ensure a clean substrate. Afterward, a 2.5 mm thick layer of LAP811 adhesive (Shenzhen Huaxun Semiconductor Materials Co., Ltd.) was spin-coated on carrier 1. Following that, the specimens were cured at 100 °C for 10 min, and the Micro-LED chips were then bonded to carrier 1.

B. Laser transfer

1. The first laser transfer

This process uses a common laser transfer technique called LLO for the decomposition of the interface layer exposed to laser radiation. Figure 2 shows a representative schematic illustration of the LLO process. The UV laser beam is incident from the sapphire and focused at the interface layer, resulting in the decomposition of interfacial gallium nitride (GaN) into gaseous nitrogen and gallium droplets.[33] The equation is as follows:

$$2\text{GaN} \rightarrow 2\text{Ga}(\text{l}) + \text{N}_2(\text{g}). \tag{1}$$

The reaction reduced the adhesion strength between the interfaces and successfully released the Micro-LED chips from the sapphire substrate onto carrier 1. However, the GaN sample, after the laser irradiation, tends to retain some material residues at the interface, such as Ga and Ga oxide. These residues were then cleaned up by using a dilute acid solution of HCl.[34]

2. The second laser transfer

The adhesive layer (LAP811) on carrier 1 contains a light-absorbing layer that absorbs the incident laser beam and exhibits a strong response to it. At the moment of laser ablation, the adhesive layer undergoes photochemical decomposition, which produces a gas impulse that causes the chip to separate from carrier 1 and fall uniformly onto carrier 2. After cleaning, a layer of TAP7510 adhesive layer (Shenzhen Huaxun Semiconductor Materials Co., Ltd.) was spin-coated with a thickness of ~20 μm. After that, the specimens were cured at 180 °C for 5 min and then served to receive Micro-LED chips. This process allows for a single-shot transfer of 6400 Micro-LED chips at a defined pitch and achieves a 100% yield after removing and repairing the damaged pixels.

Especially, it is inevitable that a trace amount of residual adhesive and particles are brought down to the surface of carrier 2 during the transfer process. This study used a special cleaning agent (Fujian Yurong Technology Co.) to clean the substrate before moving forward with the next process in order to eliminate heterogeneous pollutants that may negatively impact the subsequent bonding effect. (In the following sections, the transfer yield and transfer displacement precision are described with reference to the second laser transfer.)

C. Bonding

At this point, the Micro-LED chips have been successfully transferred to carrier 2. Through flip-chip bonding, the inverted chips can be accurately assembled onto TFTs via a micrometer-level bonding device. The indium bumps are used to connect Micro-LEDs to the TFT driver substrate mechanically and electrically.

III. RESULT AND DISCUSSION

A. Selection of ablative-type release material

First and foremost, the material selection plays a crucial role in determining the process. The laser transfer processes explored in this study pertain to specific phenomena that occur as a result of the absorption of the laser beam through different interface materials. These phenomena typically involve localized deformation, changes in phase and microstructure, melting or liquefaction, vaporization or ablation, and decomposition. The Micro-LED chips are typically released from carrier 1 to carrier 2 as a result of structural changes in the light-absorbing layer of carrier 1, which absorbs the

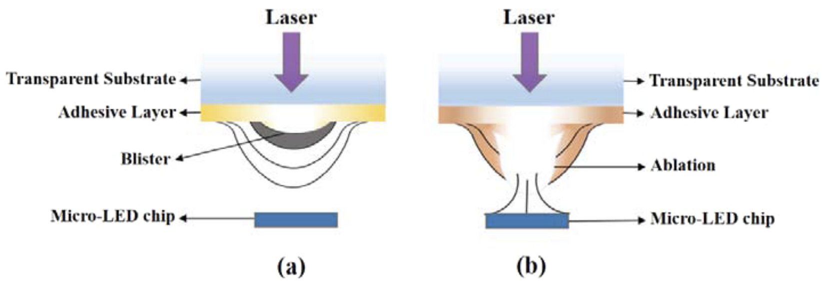

FIG. 3. Schematic diagrams of the two release materials when the laser irradiates the interface layer through a transparent substrate. (a) Blister-type release material. (b) Ablation-type release material.

incident laser beam. Carrier 1 safeguards the chip during laser irradiation, and the various reaction types at the interface have varying effects on the entire laser transfer process. Consequently, the selection of the release material for carrier 1 is a critical component of the laser transfer. To gain more insight, we performed comparative experiments between blister and ablative transfer release materials.

The schematic diagram of the interface shown in Fig. 3(a) is a kind of blister-type transfer release material. By irradiating the adhesive surface with laser light, gas is generated, which causes a bubble to appear between the adhesive surface and substrate. Although this reaction reduces the adhesion force of the adhesive surface, pushing the chip to drop, the appearance of bubbles on the adhesive surface will cause irregular diffusion, affecting the adjacent four chips. During the laser transfer, there must be spatial discrete between the chips, resulting in significant waste if 3/4 of the chips on the substrate cannot be used. Figure 4(a) shows the backside image, the frontal image of the Micro-LED chips on the blister-type transfer release material after LLO, and the discrete chip transfer image on the blister-type transfer release material. In contrast, Fig. 3(b) shows the interface schematic diagram of LAP811, an ablation-type transfer release material. Under UV light irradiation, the adhesive layer undergoes a photochemical process that directly decomposes and produces gas without creating bubbles. Therefore, there is no impact on the adjacent chips, and the chips can be transferred continuously. Figure 4(b) shows the backside image, the frontal image of the Micro-LED chips on LAP811 after LLO, and the image of continuous Micro-LED chip transfer without affecting the adjacent chips on LAP811. Clearly, this ablation-type release material LAP811 can greatly improve chip utilization.

Therefore, to address the issue of wasting chips, it is crucial to verify the feasibility and repeatability of the continuous transfer. In order to further confirm whether LAP ablation-type release material is a way to solve this problem, we performed spatially discrete transfer (i.e., intervals exist between the Micro-LED chips) and spatially continuous transfer experiments using LAP811 as the transfer release material while keeping the transfer conditions constant. Ultimately, Figs. 4(c) and 4(e) show the images of the spatially discrete transfer and spatially continuous transfer. Figures 4(d) and 4(f) show the observation of carrier 2 assuming the chips under the two methods. In conclusion, the experimental results confirm the benefits of LAP811 ablation-type material, which enables the continuous transfer of Micro-LEDs and increases the chip utilization rate.

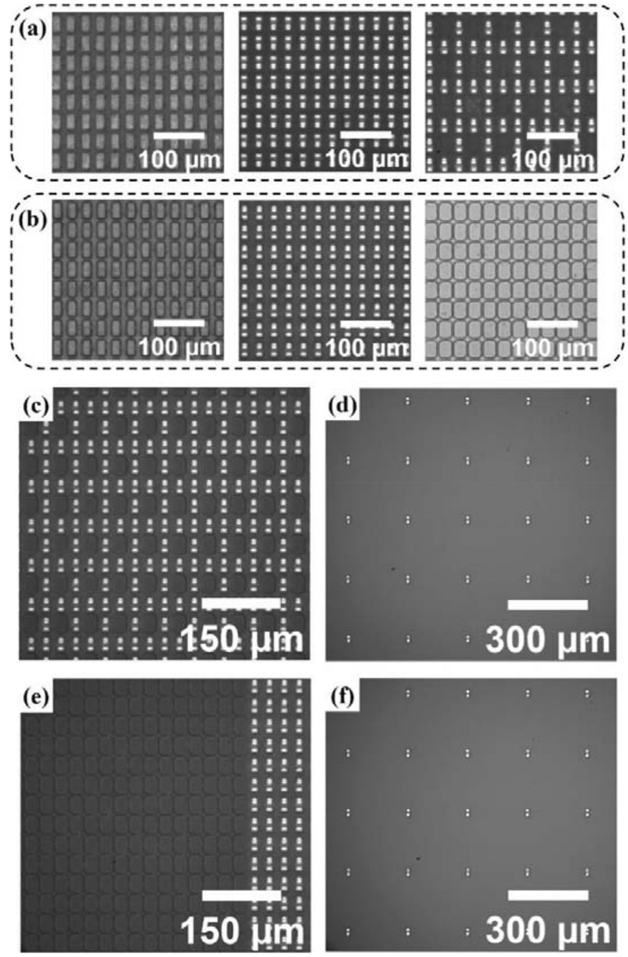

FIG. 4. (a) The left image shows the backside image of the Micro-LED chips after the blister-release material LLO. The middle image shows the frontal image of the Micro-LED chips after the blister-release material LLO. The right image shows the Micro-LED chips transferred using a spatially discrete transfer method. (b) The left image shows a backside image of the Micro-LED chips after LAP811 ablation-release material LLO. The middle image shows the frontal image of the Micro-LED chips after LAP811 ablation-release material LLO. The right image shows the Micro-LED chips transferred using LAP811 by the spatially continuous transfer method. (c) and (d) Chip images of LAP811 ablation-type release material when transferred using spatially discrete transfer and chip array on carrier 2 after transfer. (e) and (f) Chip images of LAP811 ablation-type release material when transferred using spatially continuous transfer and chip array on carrier 2 after transfer.

B. Cleaning method of carrier 2

The second laser transfer method involves transferring the Micro-LED chips from carrier 1 to carrier 2. Then, the chips are transferred from carrier 2 to the TFT driver circuit substrate using the bonding force of the metal on the TFT driver circuit substrate. For this phase, it is necessary to provide proper adhesion of carrier 2, which will ensure not only stable reception of the chips but also facilitate smooth bonding with the driving circuit substrate. This balance of avoiding difficult handling issues caused by adhesion is also a critical step in technical optimization. Ga or Ga oxide produced during the first laser transfer process, as well as a small amount of residual adhesive generated from the photochemical degradation of the LAP adhesive surface during the transfer, are easily adhered to the Micro-LED chips. Second transfer residues and particles are prone to being carried onto carrier 2, potentially causing additional complications. Therefore, we suggest immersing carrier 2 with the flip chips in a special cleaning agent to remove any residual adhesive and particles on carrier 2 following the second laser transfer. After being cleaned with deionized water, it was dried in preparation for the ensuing bonding process.

Because the Micro-LED chips are rearranged during the laser transfer process at a defined pitch, it is necessary to determine the appropriate cleaning time for both cleanliness requirements

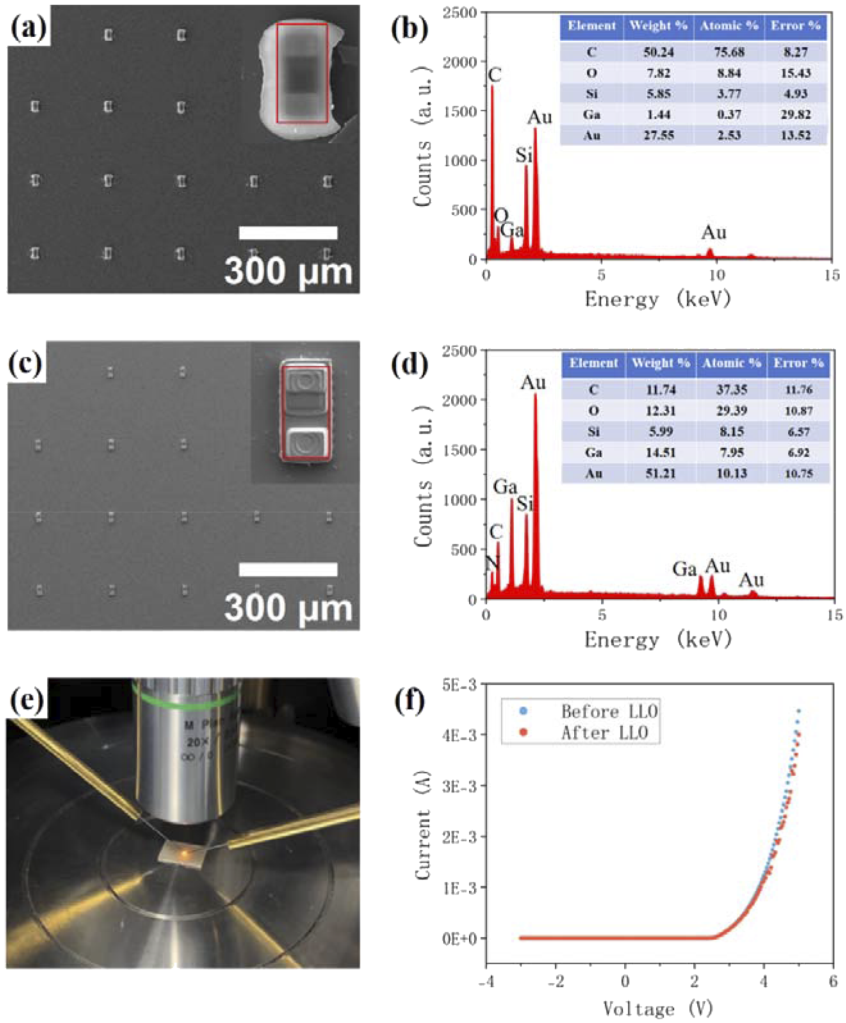

FIG. 5. [(a) and (c)] SEM images of the chip array on carrier 2 before and after cleaning. [(b) and (d)] EDS spectra corresponding to the red rectangle chip in panels (a) and (c). (e) Schematic diagram of a probe station switching on a pixel. (f) I–V characteristics of a pixel before LLO and after LLO.

and pitch standards to prevent the cleaning agent from deforming or modifying the carrier 2 adhesive surfaces. Figures 5(a) and 5(c) show the chip array on carrier 2 before and after cleaning by a special cleaning agent. As can be seen, the chips on carrier 2 before and after cleaning are in line with the standard and are arranged in the required spacing without deformation and modification. In addition, as we know, the adhesive layer contains a high carbon content. As shown in Figs. 5(b) and 5(d), the energy dispersive x-ray spectroscopy (EDS) analysis of the surface of Micro-LEDs before and after cleaning on carrier 2 shows that the carbon is 50.24% and 11.74%, respectively, indicating that a good cleaning effect was achieved. In addition, Fig. 5(f) shows the I–V characteristics of Micro-LEDs before and after the transfer process. The two curves have no discernible difference, indicating that the electrical performance did not change during the transfer process.

C. Second-transfer and repair laser parameter adjustment

In order to determine the optimal parameters for laser transfer, this study focused solely on laser energy and laser spot size. The connection between the transfer gap and the transfer precision was discovered in previous studies. Therefore, in this investigation, the transfer gap for the experiment was carefully regulated to be 20 µm. The SEM images of a single Micro-LED chip and a Micro-LED chip array are shown in Figs. 6(a) and 6(b). Figure 6(c) shows the chip structure of a Micro-LED device. The size of the Micro-LED original chips is 15 × 30 µm^2. The spacing between consecutive chips in the X direction is ~12.5 µm and in the Y direction is ~7 µm, as shown in Figs. 6(d) and 6(e). As shown in Figs. 7(a)–7(c), improper laser transfer parameters can result in chip flip-over, chip breakage, and chip missing after laser transfer. Thus, the laser energy and spot

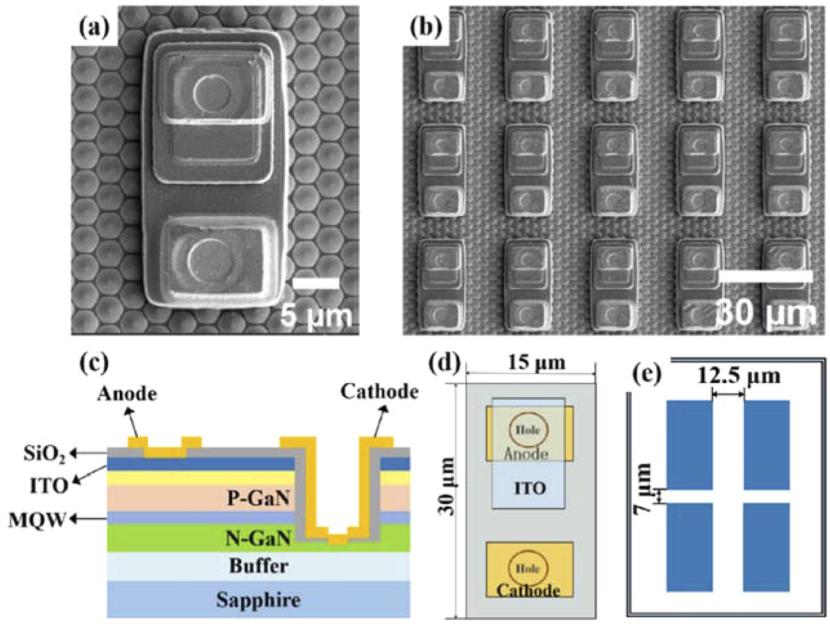

FIG. 6. [(a) and (b)] SEM images of a single chip and an array of Micro-LED chips. (c) The illustrations of a Micro-LED device. (d) Image of Micro-LED chip size. (e) The schematic of the spacing between consecutive chips.

size were adjusted in this study to achieve a transfer process characterized by minimal mistake rates, high success rates, and consistent repeatability. It was ultimately determined in this study that a higher precision and transfer yield could be achieved by controlling the laser energy within the 0.107–0.293 J/cm^2 range and using a spot size of 17 × 27.5 μm^2.

Due to the low one-time transfer yield of Micro-LEDs, detection and repair technologies are indispensable for enhancing and ensuring production yields. Identifying and quickly repairing damaged pixels is a challenging task. As shown in Figs. 8(a) and 8(b), the substrate exhibits a defective chip. For instance, if the chip is absent after LLO, only the remaining adhesive will be transferred to carrier 2. Similarly, the chip may exhibit flipping or fracturing because of a selection of inappropriate parameters throughout the process. This study utilized automatic optical inspection (AOI) technological advances to detect and locate damaged chips, enabling their targeted removal and subsequent repair at the site of the defect. Our experimental results suggest that a laser with a wavelength of 532 nm and an incident laser fluence of ~0.4 J/cm^2 was utilized to eliminate the residual adhesive. In addition, a laser with a wavelength of 532 nm and an incident laser fluence of 0.08 J/cm^2 was utilized to eliminate any damaged chips. Afterward, the position coordinate file is loaded into the laser repair equipment to carry out laser repair, achieving high-yield laser transfer without affecting the integrity of the chips. The images of the chips after defect removal and laser repair on carrier 2 are shown in Figs. 8(c) and 8(d). Figure 9(a) shows the chip array that has been repaired and cleaned on carrier 2, which has a transfer yield of 100%. It is important to note that the chip array used in this study is 80 × 80; therefore, the condition of the chips in the other areas of carrier 2 is exactly the same as what is shown in

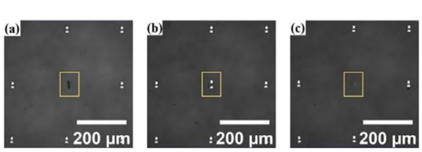

FIG. 7. (a) Image of chip flip-over. (b) Image of chip breakage. (c) Image of chip missing.

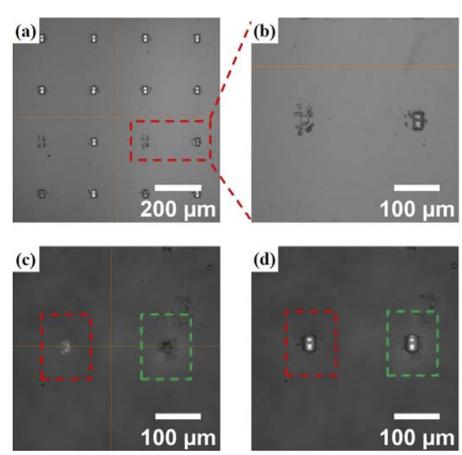

FIG. 8. [(a) and (b)] Images of the location of the damaged chips. (c) Image after laser removal of the bad pixels. (d) Image after laser repair.

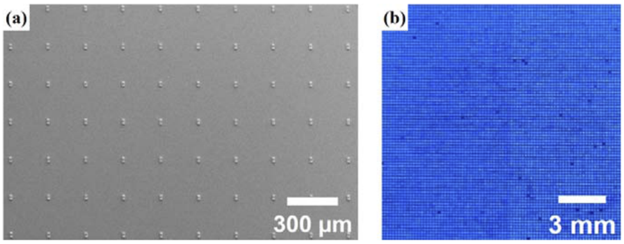

FIG. 9. (a) Image of the chip array after repairing and cleaning on carrier 2. (b) The image of the device turned on.

this image. Figure 9(b) shows the final display that is working after carrier 2 was bonded to the TFT driver circuit board.

IV. CONCLUSION

In this study, we use laser transfer technology as a primary solution and use ablation-type transfer release material that improves chip utilization over blister-type release materials. This study combines measurement of laser transfer parameters, detection, and laser repair technology to improve the transfer effects. Finally, we successfully achieved a transfer yield of ~100% and a cumulative transfer displacement of less than 1 μm in the Micro-LED flip-chip array. The receiving substrate underwent a cleaning process to eliminate any remaining adhesive residue, leading to an increased bonding efficiency between the chip and the TFT driver circuit board. Most importantly, this study was highly reproducible, which suggests further research into laser transfer for mass transfer, particularly applied to boost commercial applications.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Yujie Xie: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Software (equal); Supervision (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Xin Lin**: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal). **Taifu Lang**: Conceptualization (equal); Methodology (equal); Supervision (equal); Validation (equal). **Xiaowei Huang**: Supervision (equal); Validation (equal). **Xuehuang Tang**: Data curation (equal); Validation (equal). **Shuaishuai Wang**: Methodology (equal); Validation (equal). **Chang Lin**: Data curation (equal); Methodology (equal). **Kaixin Zhang**: Investigation (equal). **Jie Sun**: Conceptualization (equal); Visualization (equal). **Qun Yan**: Funding acquisition (equal); Investigation (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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