Advanced Integration of RGB MicroLEDs Enabled by Micro-Transfer Printing

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Abstract

Micro-displays using RGB micro-LEDs grown on Si substrates, each colour based on InGaN materials were developed. To improve the forward emission, micro-LEDs are integrated onto reflective cavities coupled with microlenses, which enables engineering of far field patterns. We also demonstrated 2-sided connections to the LEDs on glass substrates through either wrap-around electrodes or through-holes, to facilitate more compact packaging and enable seamless large displays.

Author Keywords

InGaN micro-LEDs; Micro-displays; Micro-transfer printing; Reflective cavities; Microlenses; Wrap-around electrodes; Through-glass-vias.

1. Introduction

The rapid development of micro-light-emitting diode (micro-LED) technology has revolutionized the field of microdisplays, offering significant advantages over traditional display technologies such as organic LEDs (OLEDs) and liquid-crystal displays (LCDs). Known for their high brightness, low power consumption, and superior color performance, micro-LEDs are becoming increasingly attractive for a wide range of applications, including wearables, augmented reality (AR), virtual reality (VR), and automotive displays (1,2). These displays leverage individual, emissive micro-LEDs (InGaN for blue/green, AlGaInP for red) to produce vibrant, high-contrast images with exceptional color accuracy and scalability. One issue is that the traditional AlGaInP-based red LEDs suffer significant efficiency drop when the devices shrink to the micron scale, owing to the strong surface recombination issue. Recently, InGaN-based red LEDs show great promise as efficient red light sources, with suppressed surface loss reported (3,4). The InGaN materials with potentially high efficiency and thermal performance, not only make them ideal candidates for the red segment of RGB microdisplays, but also provide the advantage of fabricating the red, green and blue LEDs based on the single and common material system.

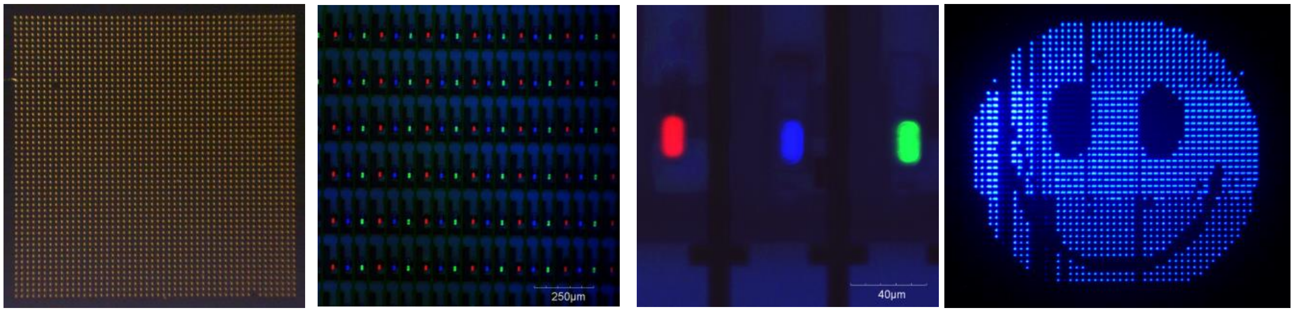
Another critical challenge in the realization of large-scale RGB microdisplays lies in the precise integration of the different colored micro-LEDs onto the display substrate. This challenge has been effectively addressed through micro-transfer printing, an emerging technology that enables the mass transfer of individual micro-LEDs onto substrates with high yield and alignment accuracy. Micro-transfer printing has demonstrated its potential for large-area integration, allowing for the precise placement of micro-LEDs with minimal damage, high uniformity, and low defect rates (5).

In this work, we will discuss the transfer printing techniques for InGaN-based red LEDs, the light management strategies via reflective trenches and microlenses, and the 2-sided connection approaches.

2. Microdisplays enabled by micro-transfer printing

Based on the micro-transfer printing technology, we have previously demonstrated micro-displays on the glass substrate, using InGaN-based blue and green LED-on-Si and AlGaInP-based red LEDs, as shown in Figure 1. Wafer-scale fabrication and releasing technologies were developed for RGB micro-LEDs respectively. For releasing of blue and green LEDs, tetramethylammonium hydroxide (TMAH) solution was used to undercut a thin Si layer at the top of the substrate, while for red LEDs, the high-Al-content AlGaAs was used as sacrificial layers and undercut by potassium iodide and iodine solution ($KI/I_2/H_2O$).

Using a 50 x 50 arrayed stamp (1x1 cm^2) made of patterned polydimethylsiloxane (PDMS), each print containing 2500 devices was realised. A yield of 99.92% for the total transfer printing process was successfully demonstrated, as shown in



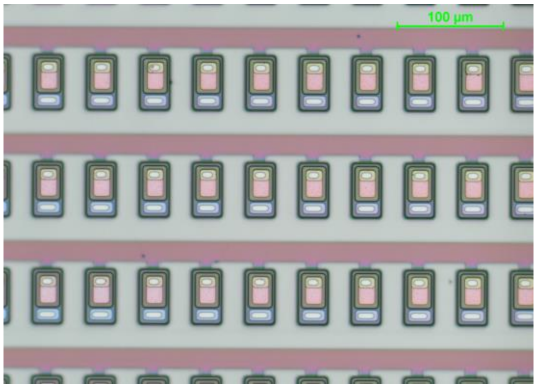
(a) A single print (b) RGB microdisplays (c) A RGB pixel (d) 1x1 cm^2 mono display

Figure 1. (a) A single print of micro-LEDs using a 50x50 arrayed stamp. (b) Fluorescence image of the integrated RGB micro-LED display. (c) A RGB pixel containing InGaN blue and green LEDs and an AlGaInP red LED. (d) Demonstrated 1x1 cm^2 micro-display.

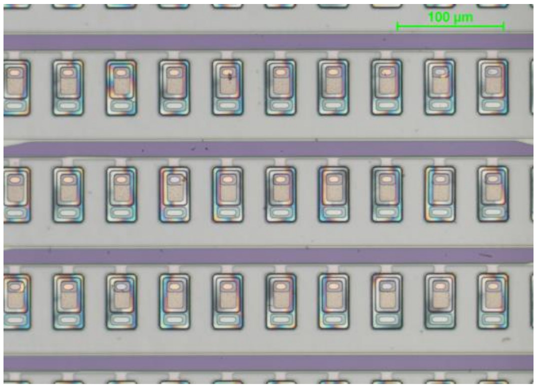
Figure 1(a). The individual RGB colour arrays were obtained by picking up the LEDs from three different wafers and printing onto the same glass substrate, exhibiting the pixel pitch of 200 µm and the resolution of 127 ppi (RGB). The metal tracks in rows and columns were finally deposited on the substrate to drive the LEDs to show the displays. Further development of active-matrix controlled displays based on the Indium Gallium Zinc Oxide (IGZO) transistors on glass was also reported (6).

3. Transfer printing of InGaN-based red micro-LEDs

Working with InGaN-based red emitters are highly desired, not only for their potential high efficiency, but also for a common fabrication process as their blue and green counterparts, which could streamline the whole integration process. Here, utilising the InGaN-based red LEDs grown on 200 mm Si substrates, we successfully applied the same fabrication techniques as we did for blue and green LEDs. Benefiting from the single material system, processes such as the metallisation for P and N contacts, the thermal annealing, the plasma etch process and undercut etching are identical for all the RGB micro-LED wafers.



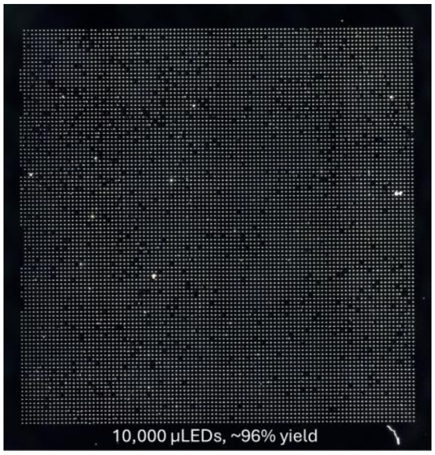
(a) InGaN red micro-LEDs prior to release etch



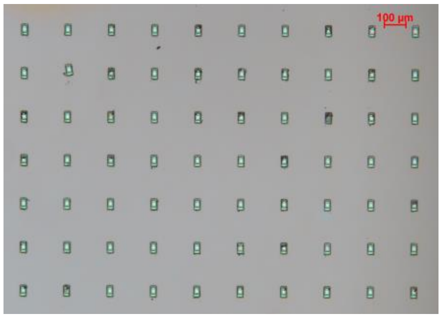
(b) After release etch in 5% TMAH

Figure 2. Optical images showing the InGaN-based red micro-LEDs on Si substrate (a) prior to release etch and (b) after release etch.

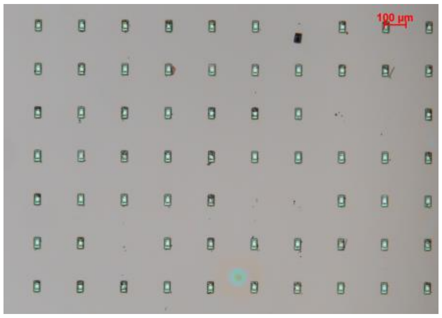
The anchored red LEDs, with the size of 30 x 50 µm^2, are depicted in Figure 2. After the TMAH etching, the areas beneath the LEDs were undercut completely while the long anchors (aligned to the [1-10] direction) were only etched slightly. The micro-LEDs are suspended on the surface but supported firmly by the tethers/anchors. Due to the air gap underneath the devices, the interference can be observed from the optical images, showing a slight tilt of the devices.



(a) Printed 10,000 InGaN red micro-LEDs



(b) Good regions with high yield



(c) Regions with poor yield

Figure 3. Micro-transfer printing of InGaN red micro-LEDs. (a) Four prints containing 10,000 devices. (b) Representative good regions. (c) Representative poor yield regions.

After the releasing etch, we further demonstrated the micro-transfer printing of these red LEDs using the 50 x 50 arrayed stamp. In our initial tests, a 100 x 100 LED array with the size of 2 x 2 cm^2 was printed successfully, as shown in Figure 3. The printing yield was estimated to be 96% approximately. The main reasons responsible for the printing failures include (1) the incomplete undercut etching of the LED wafer (‘source’), (2) the defects on the source, and (3) the defects on the new receiving wafer (‘target’). Note that the defects on the source could originate from either the growth defects or the defects introduced during the device fabrication process.

Further investigation on the source revealed that most of the devices were picked up successfully by the stamp, except for very few ones remaining due to the incomplete undercut etching. By examining different printing regions in the target, it was observed that some residues were left at the location of the missing devices. These residues, probably stemming from the by-products of the undercut etching such as the cracked tether material, were stuck underneath the devices and prevented the good adhesion of micro-LEDs on the target during the printing process. However, it is expected that the yield can be significantly improved if a defect-free fabrication process with clean undercut etching is achieved.

4. Light management with cavities/microlenses

For GaN-on-Si LEDs, due to the strong absorption of the Si substrate in the visible ranges, removing the substrate is required to obtain higher light output power. The micro-transfer printing provides a flexible approach to do this, allowing LEDs to be placed on any non-absorbing substrate, such as glass or reflective wafers.

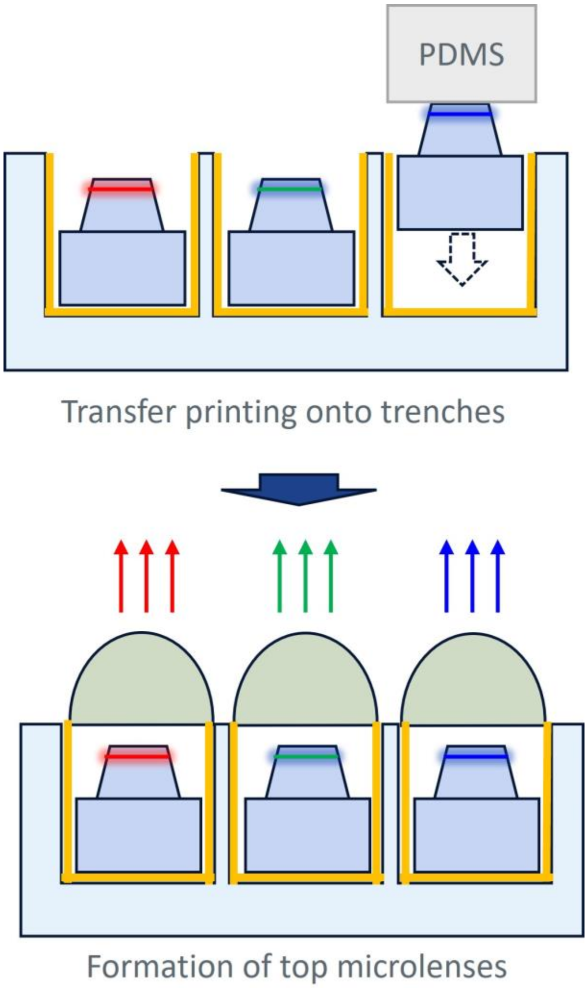


Figure 4. Schematics of printing micro-LEDs in the reflective cavity coupled with microlenses on the top.

In many applications such as AR/VR displays, a collimated light emission from the LEDs is preferred, to facilitate the efficient light coupling to other optical components. To maximize the light output perpendicular to the surface, we proposed to integrate micro-LEDs onto reflective cavities (or trenches) and couple them with microlenses on the top. The fabrication process is shown schematically in Figure 4.

- First, create reflective cavities on the target wafers. For example, form Si trenches with slanted sidewalls and coat them with reflective metals.
- Second, place the RGB micro-LEDs into the cavities sequentially via micro-transfer printing, and deposit the connecting metals.
- Third, planarize the surface and form the microlenses on top of LEDs.

It has been demonstrated in our previous report (7) that transfer printing enabled LED integration in the reflective cavities can improve the forward light output by ~1.8 times. Such significant improvement has been attributed to the cavity effect, which can collect the light from the device sidewalls and redirect to the surface. To collimate the beam profile further, the microlenses, made of low loss material, can be placed on top of LEDs. The shape of the microlenses, including the curvature and height, can be engineered to match the emission patterns of LEDs in the cavity, which can reduce the divergence angles to the maximum extent possible.

5. Driving micro-LEDs through wrap-around electrodes or through-holes

One challenge for miniaturizing the micro-displays is the connection with the electronic controllers, which usually requires fanout metal tracks for easier and reliable connections. A promising approach is to distribute the connections to the backside of display substrates, through either the wrap-around electrodes or through substrate holes, as shown schematically in Figure 5(a). This 2-sided connections could provide the following advantages:

- Compared to the 2-dimensional packaging, by directing the connection to another side of the substrate, a vertically-stacked packaging between the displays and other electronic chips can be possible, leading to a more compact and miniaturized system
- It also enables seamless large displays when tiling multiple units. For instance, when two display panels were tiled together, if the gap between the edge pixels of the two panels can accommodate the wrap-around electrodes, then the large display will be seamless.

Here we successfully demonstrated the electrical driving of LEDs via the through-glass-vias, as shown in Figure 5(b). The blue and green micro-LEDs were transfer-printed onto one side of the glass substrate and then connected with metal tracks to the metallized vias, which were connected to the larger metal pads on another side of the glass. To test the devices, the glass substrate was placed upside down to allow probe contact on the backside, and a camera was placed underneath the sample to capture the electroluminescence images.

The current-voltage characterization of the printed blue and green LEDs was carried out. It showed that there was additional series resistance from the metal tracks including the through-glass-vias. This can be further minimized by optimizing the design as well as the metallization process.

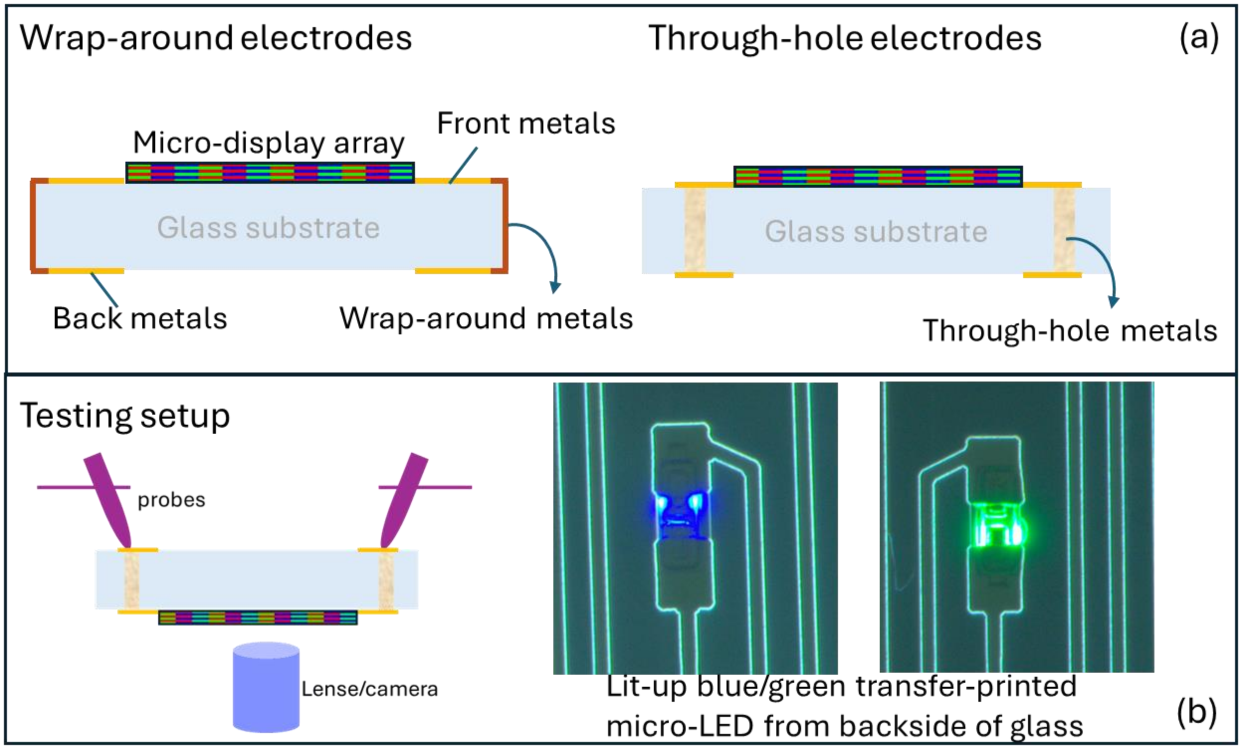


Figure 5. (a) 2-sided connection strategies either through the wrap-around electrodes, or the through-holes. (b) Electrical driving of printed LEDs on glass through the through-glass-vias. Left: the schematic setup of testing. Right: lit-up images of blue and green LEDs.

6. Conclusion

Micro-transfer printing has been proven to be a promising mass transfer technology for displays. Built on our previous development of transfer printing with traditional LED-on-Si (B/G) and AlGaInP LEDs (R), we successfully demonstrated the transfer printing of InGaN-based red LEDs on Si. By analyzing the yield of the printing process, we revealed that the residues resulting from the undercut etching process contribute to most of the printing failures. To improve the light collection from the surface and obtain the reduced divergence, we proposed to use transfer printing to place LEDs into a cavity structure coupled with a microlens. We also demonstrated the electrical driving LEDs through the through-glass-vias, which along with wrap-around electrodes, could be promising strategies to achieve miniaturized packaging and seamless displays.

7. Acknowledgement

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