Elastomer Stamp Mass Transfer of PixelEngine Devices for High-Performance MicroLED Displays

Christopher A. Bower, Salvatore Bonafede, Erich Radauscher, Andrew Pearson, Carl Prevatte, Ben Keller, Brook Raymond, Tiffany Weeks, Geoff Bradshaw, Erik Vick, Chris Verreen, David Kneeburg, Nikhil Jain, and Matthew A. Meitl

chris@xdisplay.com
X Display Company, Inc., Research Triangle Park, NC, USA
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ABSTRACT

Mass transfer technologies provide display-makers the opportunity to use high-performance devices formed on wafers inside the pixel array to achieve enhanced display performance. Mass transfer using patterned elastomer stamps is a high yield, high throughput, accurate and cost-effective technique for assembling microLEDs and microICs onto display panels.

1 Introduction

A 2021 report [1] describes strong industry-wide momentum toward displays that utilize microLEDs. Patent filings are growing at 86% compound annual growth rate, and the report estimates that more than 6 billion US dollars have been invested in microLED display efforts. Despite technological breakthroughs on many fronts, there persist questions regarding the mainstream applicability of microLED displays. The future scale of the microLED industry depends on the display manufacturing cost, and the manufacturing cost depends on a mass transfer technology that can assemble very small microLEDs with high yields and throughput.

2 Discussion

Pioneered in the 2000s [2], elastomer stamp mass transfer, also called micro-transfer printing, is the foundation of several industrialization efforts [3]. In 2009, a transparent, deformable, microLED display was demonstrated using elastomer stamp mass transfer [4]. Subsequent reports described full-color 127 and 254 PPI passive-matrix displays using 8 x 15 μm^2 microLEDs, where the 127 PPI display exhibited over 60% transparency [5], and a 127 PPI active-matrix display that utilized elastomer stamp transferred microICs to drive the microLEDs [6]. Fig. 1 is a photograph of a transparent, full-color, active-matrix 5.1” 70 PPI microLED display with a microIC-enabled 14-bit PWM driving architecture [7]. Fig. 2 shows the measured light transmission through the display versus wavelength. The inset optical micrograph shows the pixel design which includes redundant microLEDs and microICs. The display is made on glass with two metallization levels [6] and contains no thin-film transistors, transparent conductive oxides, or anti-reflection coatings.

Elastomer stamp mass transfer is performed with equipment designed to move and align the stamp relative to the device source and destination substrates. Fig. 3 is a photograph of a mass transfer tool designed and built to populate 300 mm substrates and is based on a substrate platen with 600 mm x 800 mm stage travel. Fig. 4 is a cross-section depiction of the transparent and compliant elastomer stamp with surface relief features, called posts, for contacting the devices. The elastomer stamps are produced using low-pressure injection molding and lifetime studies demonstrate that stamps are robust to tens of thousands of transfer cycles [8]. The transfer stamp is attached to a printhead with four motion axes (Z, Θ, Tx, Ty). Machine optics on independent X, Y, and Z stages aligns the stamp to the device source substrate and aligns the picked-up devices to the destination substrate before transfer. After initial set-up, the printer performs automated transfer sequences that include touching down onto a roll-fed tape cleaning station before returning to the source substrate to begin the next transfer cycle. The transfer process uses no heaters, liquids, or gases.

A 2010 paper demonstrating microIC backplanes for active-matrix OLED displays reported a microIC transfer yield of 99.95% and a 3σ placement accuracy of +/- 1.5 µm [9]. More recently, microLED display prototyping efforts have achieved 99.99% transfer yields for both 3 x 10 μm^2 and 8 x 15 μm^2 microLEDs [5 – 7]. In another study, 70 x 35 μm^2 silicon nitride chips were transferred at 99.99% yield using stamps with 64 x 64 and 128 x 128 post arrays [10]. These high transfer yields are achieved in research labs, and higher transfer yields are anticipated in volume manufacturing environments.

The mass transfer throughput of a single printhead is a function of the number of devices transferred per stamp cycle and the time required for the complete transfer cycle. The number of devices transferred per cycle is a function of the device density and the stamp size. Fig. 5 is an electron micrograph of a source substrate with transfer-ready 24 x 20 μm^2 devices on 30 x 30 µm pitch designed for mass transfer throughput studies. The devices are fabricated using a silicon-on-insulator (SOI) substrate and are undercut by anisotropic etching with a hot aqueous base [11]. These devices were transferred onto a 200mm glass wafer using a stamp designed to transfer a 500 x 500 array of devices at 60 µm pitch, 250,000 devices per stamp cycle. Fig. 6 shows screen-captures from the machine optics during the mass transfer cycle. The optics field of view shows a 3 x 3 stamp post section of the 500 x 500 post stamp. The cycle begins as the elastomer stamp contacts the transfer-ready device array on the source substrate. The devices are transferred from source to stamp when the stamp is rapidly lifted from the substrate [12]. The populated stamp is positioned over and aligned to marks on the destination substrate using automated pattern recognition tools. The devices are contacted to the resin-coated destination glass wafer, and the stamp undergoes a lateral shear process [13] before lifting away from the transferred devices. The middle image in Fig. 6 shows that the devices are completely transferred to the glass substrate twelve seconds into the transfer cycle. Next, the stamp is positioned and contacted to the roll-fed cleaning tape, before returning to the source substrate and indexing to the next device array to initiate the next cycle. Fig. 7 is a photograph of a 200 mm glass wafer after sixteen print cycles with the 30 x 30 mm^2 stamp that transfers 250,000 devices per cycle. Using this stamp, four million devices are transferred in under eight minutes, equaling a device throughput greater than 30 MUPH. Ongoing work will demonstrate single printhead throughputs exceeding 100 MUPH using larger stamps and reduced cycle times. Stamps populated with microdevices can move at high speeds during the transfer cycle, and the device pick-up and transfer processes do not require long dwell times. This kinetic mass transfer process occurs at ambient temperature and pressure. Today, cycle times of 25 seconds are routine, and projections of future cycle times are less than 10 seconds.

A further strategy to increase mass transfer throughput is to first transfer the microLEDs onto an intermediate packaging substrate [14]. This allows the microLED mass transfer to occur with higher device densities and enables the second transfer onto the display substrate to leverage larger stamps. Fig. 8 is an electron micrograph of a printed microscale package, called a PixelEngine™ RGB device, that contains discrete red, green, and blue microLEDs [15]. This device can be fabricated on large format, 300 mm diameter, silicon wafers and allows the display manufacturer to use larger scale transfer stamps for the mass transfer of PixelEngine™ RGB devices onto the display panel. Table 1 models the throughput implications for manufacturing a 25" diagonal 169.3 PPI display using PixelEngine™ RGB devices built on a 30 µm pitch. A 50 x 50 mm^2 stamp transfers ~2.78M microLEDs per stamp cycle and equates to ~ 500 MUPH assuming a 20 sec process cycle time. A 200 x 200 mm^2 stamp transfers ~1.78M PixelEngine™ RGB devices at 150 µm pitch, yielding 320 million devices transferred per hour. Each device contains three microLEDs, so the effective microLED transfer rate is 960 MUPH for a single printhead with a 20 second cycle time.

3 Conclusions

Practical mass production of microLED displays depends on the assembly time required to transfer billions of discrete wafer-level microdevices. Mass transfer with scalable, transparent, elastomer stamps on motion-plus-optics platforms provides a path to transferring hundreds of millions of units per hour. A key to high throughput is increasing the number of devices transferred per stamp cycle. Fabricating PixelEngine™ devices on intermediate substrates delivers strategies for optimizing the devices per stamp cycle. A higher density of microLEDs is transferred per unit area onto the intermediate wafer, and the intermediate wafer supports a larger stamp that enhances the UPH onto the display substrate. In a modeled process utilizing intermediate substrates, 25" diagonal 169.3 PPI displays are populated in less than three minutes of transfer time per display.

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Fig. 1 Photograph of a transparent 320 x 160 70 PPI microLED display in front of toy dogs.

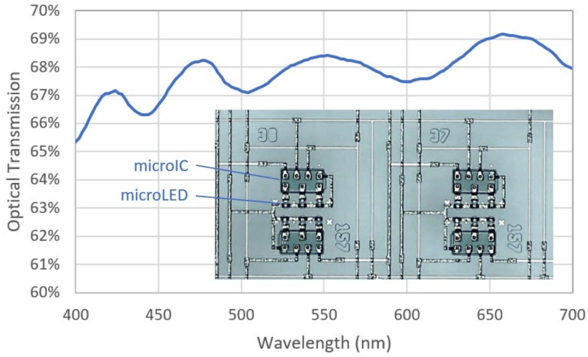

Fig. 2 Measured optical transmission versus wavelength of the 70 PPI microLED display shown in Fig. 1. The inset is an optical micrograph of two pixels in the display.

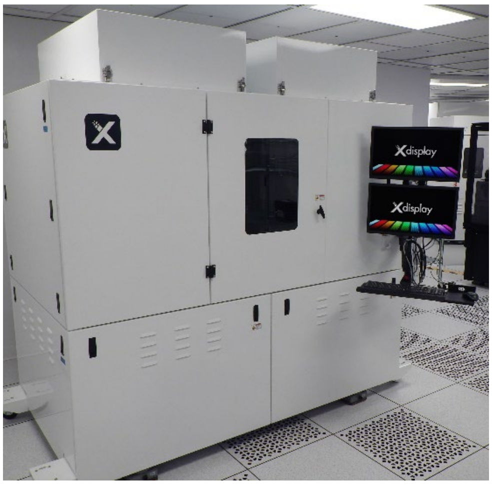

Fig. 3 Photograph of a MTP300 transfer printer with 600 mm x 800 mm stage travel.

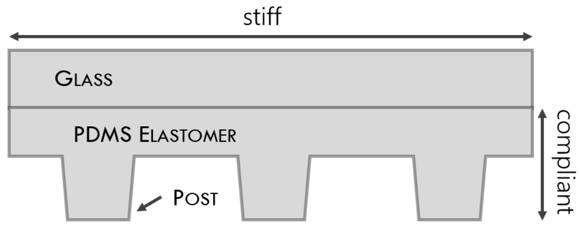

Fig. 4 Cross-section depiction of an elastomer transfer stamp.

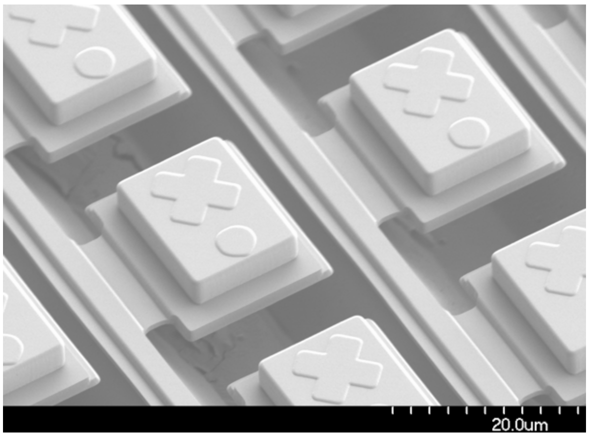

Fig. 5 Scanning electron micrograph of the print-ready devices used for throughput studies.

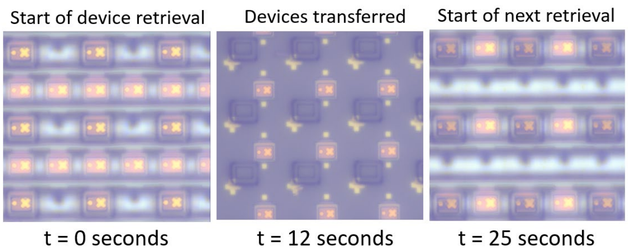

Fig. 6 Screen captures from the printer machine optics depicting the mass transfer sequence using the 500 x 500 post array transfer stamp.

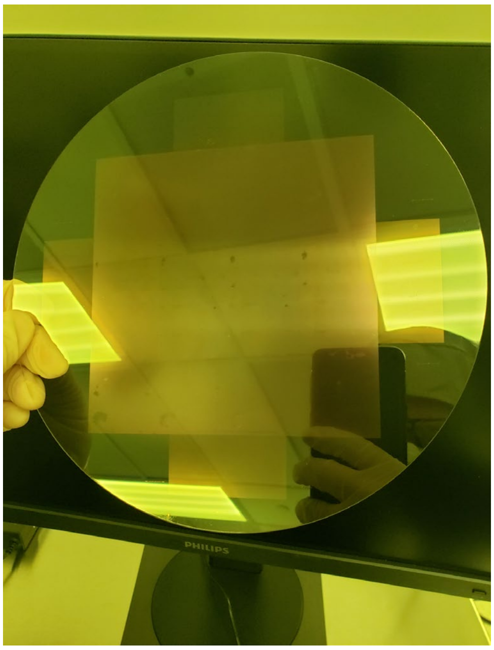

Fig. 7 Photograph of a 200mm glass wafer populated with 4M devices in under 8 minutes.

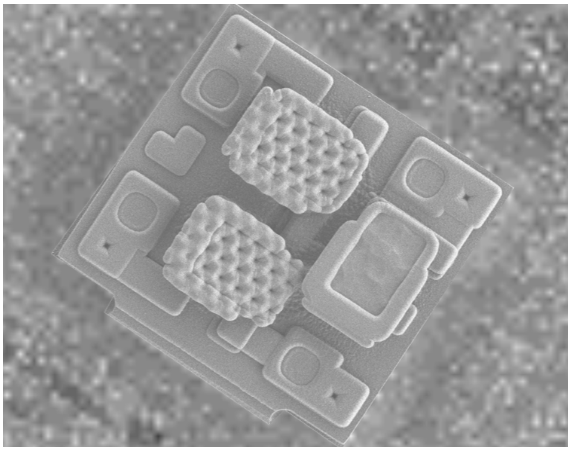

Fig. 8 Electron micrograph of a transfer printed PixelEngine^{TM}RGB device.

	MicroLED Wafer-to-PixelEngine^{TM} Wafer	PixelEngine^{TM}Wafer-to-Display Panel
Post Array Dimensions (mm x mm)	50 x 50	200 x 200
Stamp Post Pitch (µm)	30	150
Devices per Stamp Cycle (Millions)	~ 2.78	~ 1.78
Throughput (MUPH) @ 20 sec/cycle	~ 500	~ 320*
Printheads for 1M displays per year	4	2

* 960 Million microLEDs transferred per hour!

Table 1 Modeled transfer throughputs and printhead requirements for the annual production of 1M 169.3 PPI 25" diagonal displays [14].