Making microLED Displays

Mass transfer with elastomer stamps for microLED displays.

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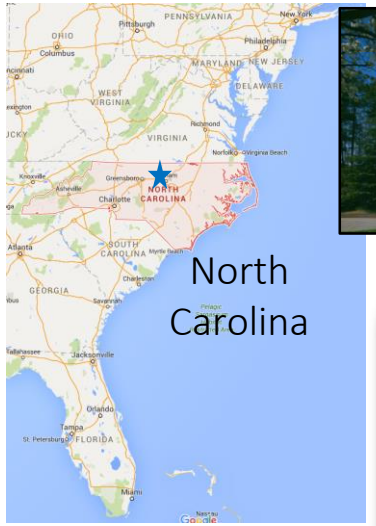
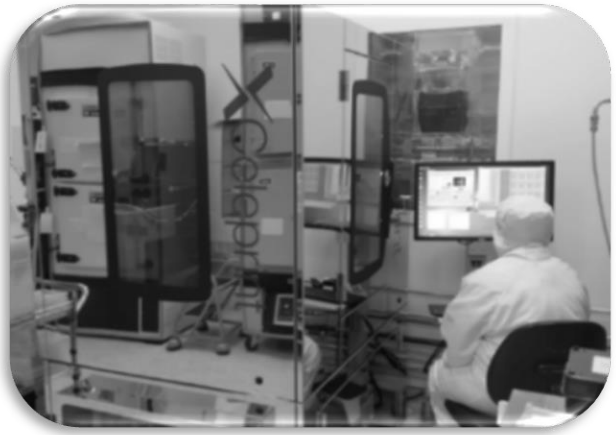
Mass transfer with elastomer stamps for microLED displays.

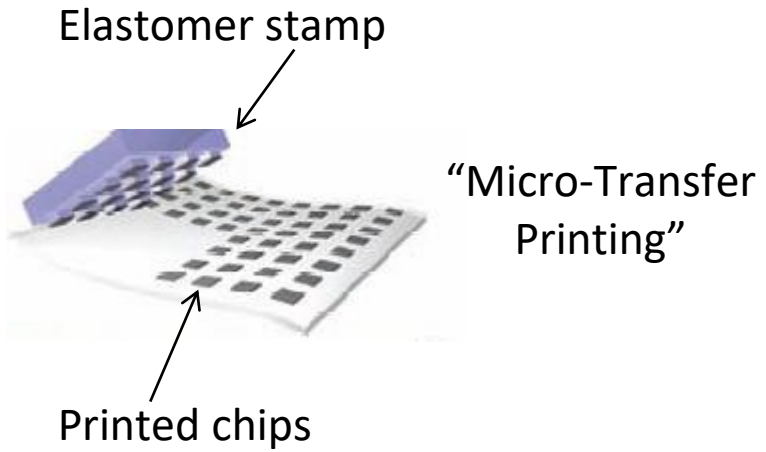
1. Introduction
2. Micro-Transfer Printing
3. MicroLEDs & Displays
4. Examples of Printed Displays
5. Manufacturing Strategies

X-Celeprint





- develops and licenses advanced assembly solutions.
- is headquartered in Cork, Ireland. Offices and facilities in the Tyndall National Institute.
- has a wholly-owned subsidiary located Research Triangle Park, North Carolina.



Micro-Transfer-Printing Timeline

Micro-transfer printing (µTP) is developed in Prof. John Rogers group in the mid-2000s.

Semprius is formed and spun-out of the University of Illinois in 2006 to commercialize µTP.

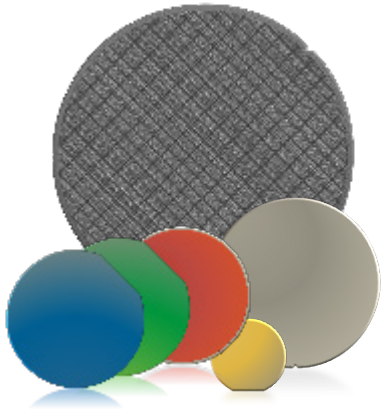
Semprius pursues concentrator photovoltaics (CPV) using printed 3J cells from 2007 to 2016.

X-Celeprint forms and acquires rights to µTP in 2013.

X-Celeprint develops and licenses advanced assembly solutions.

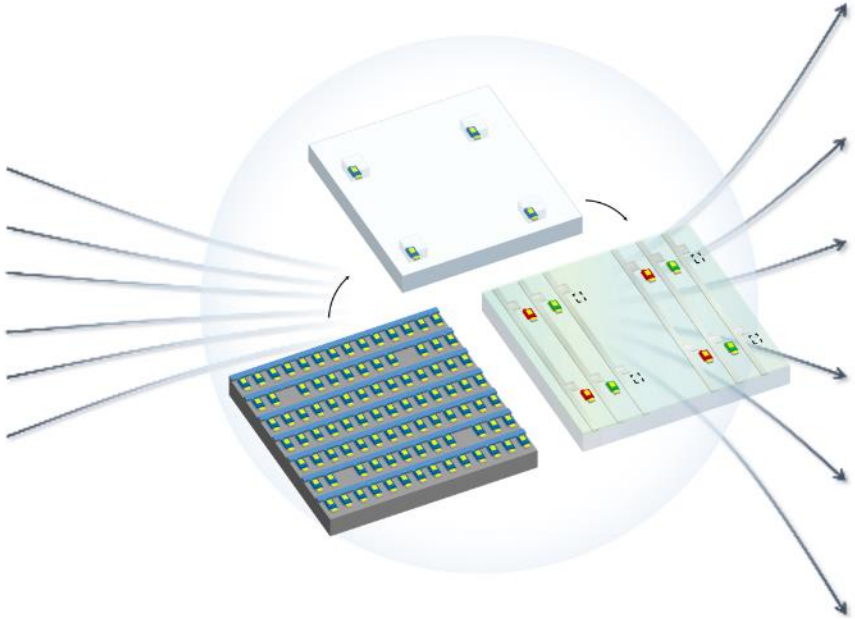
…a bridge from wafer to wherever…

the best devices

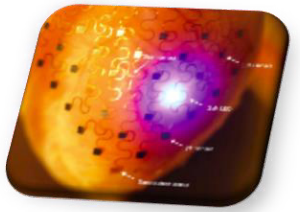


Wafer Fabricated Devices
Single-crystal
Fine lithography
(ICs, LEDs, Lasers, etc…)

rapid & precise assembly



novel hybrid formats & cost structures

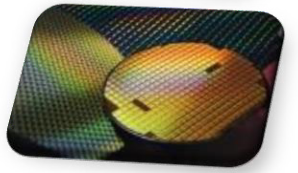


wearable
med-tech

plastics
flexible

large-format

thermal
low-cost



heterogeneous
3-D

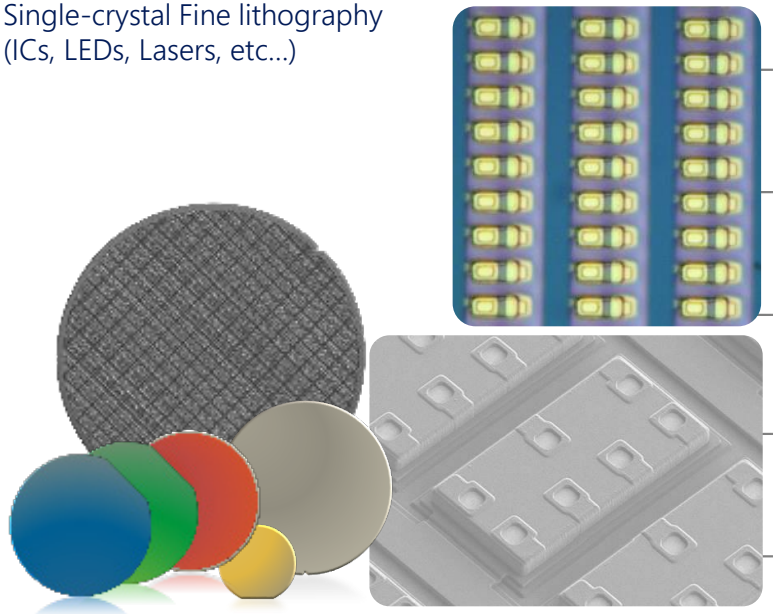
The best materials for the best displays

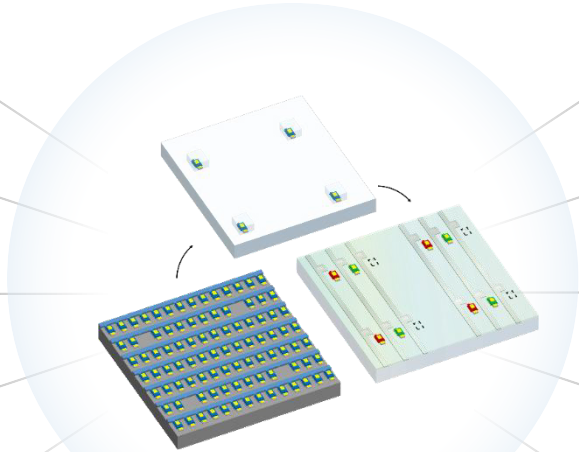
The materials identify the display. The best displays will use the best materials.

Brightest, fastest, most efficient, extra-functional, multi-sensory, computational “systems on a panel”.

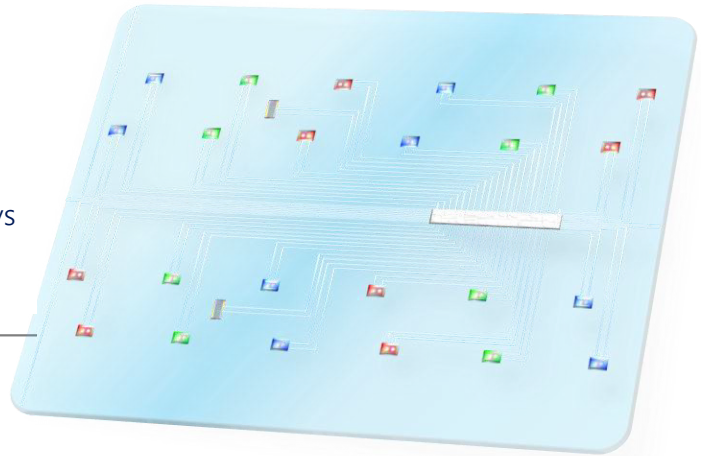
Bridging the gap between wafer and panel is the way to get the best displays.

Wafer Fabricated Devices
Single-crystal Fine lithography
(ICs, LEDs, Lasers, etc…)





Advanced displays
of all sizes:



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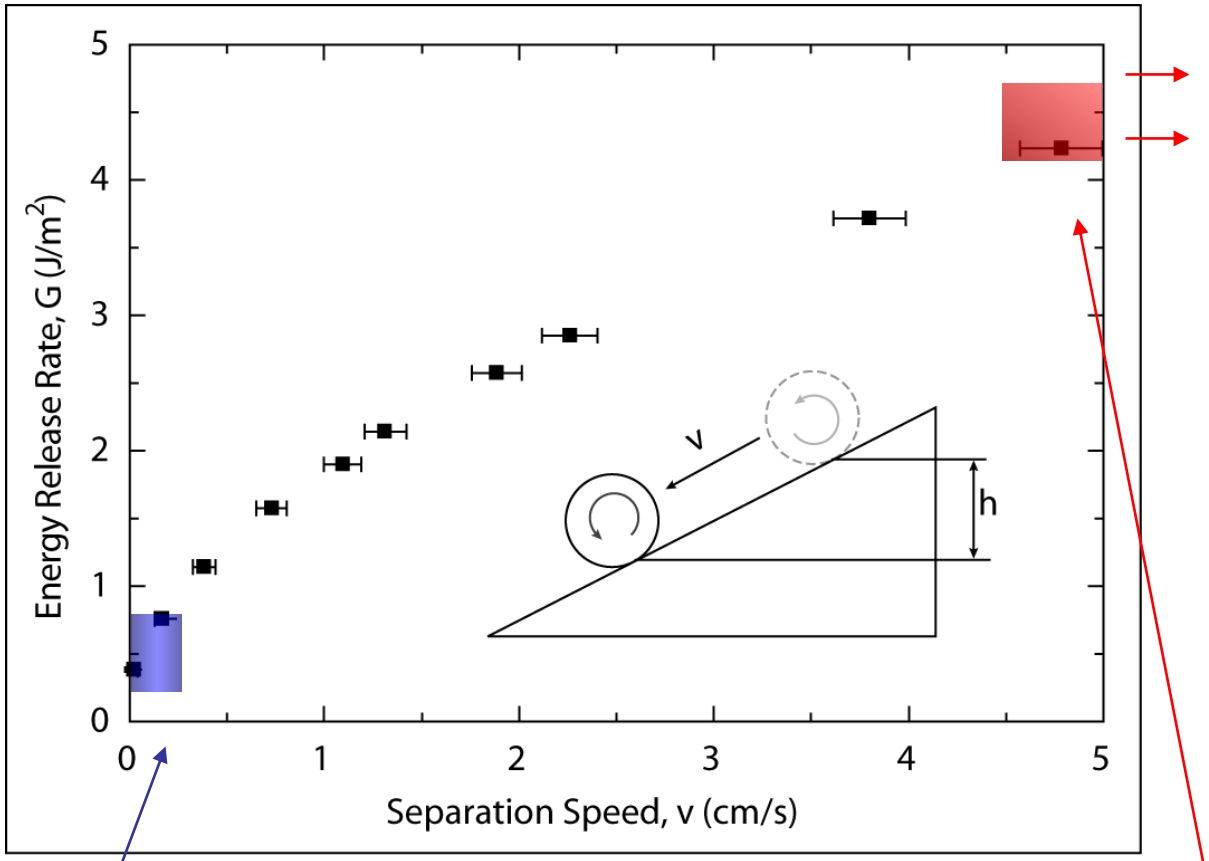
Rate Dependent Adhesion

Terminal Velocity on an Inclined Plane



printing regime

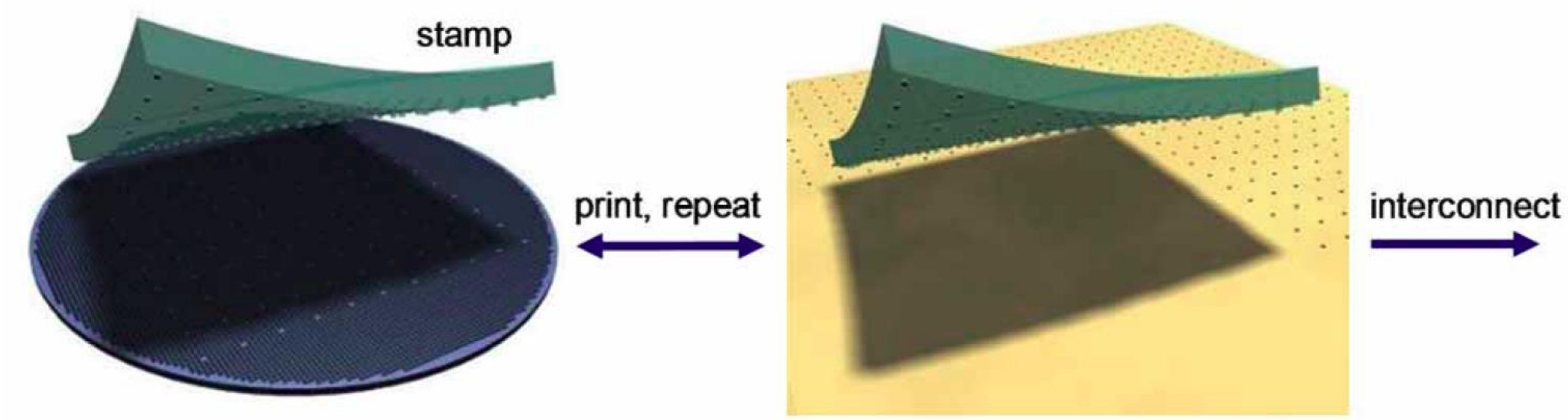
retrieving regime

Nature Mater **5**, 33 (2006).

(actual speeds/energies are system-specific)

Rapid, Precise Microdevice Assembly via Printing

1. Form undercut microdevices, anchored at endpoints
2. Transfer them to a target substrate by elastomer stamp printing
3. Interconnect to form systems



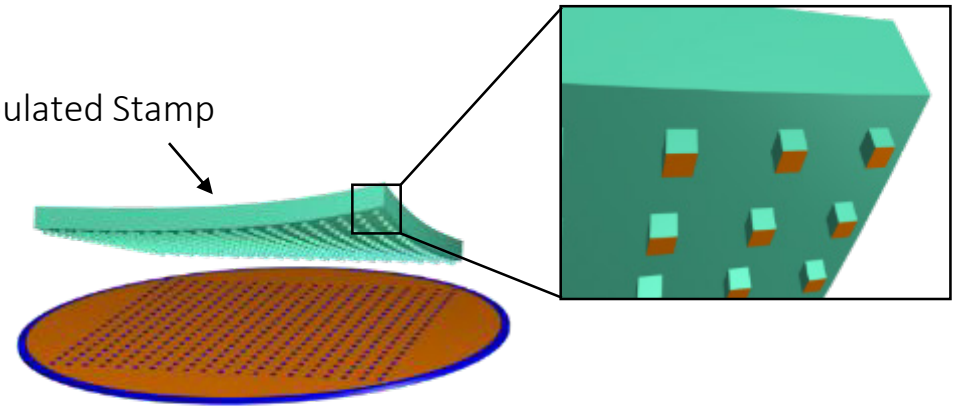
A ***source*** wafer provides the micro-devices

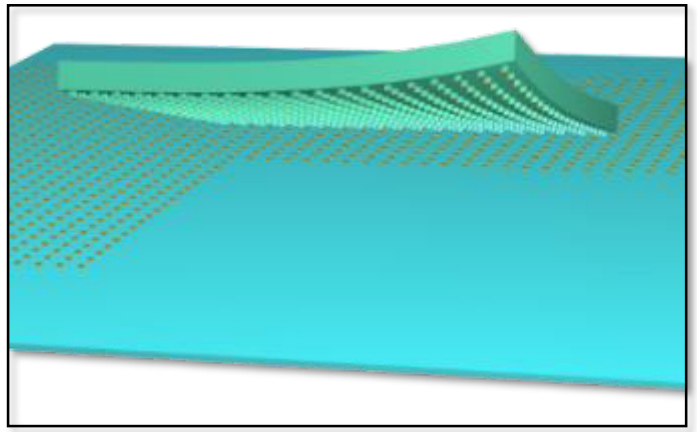
The micro-devices are assembled onto a ***target*** substrate

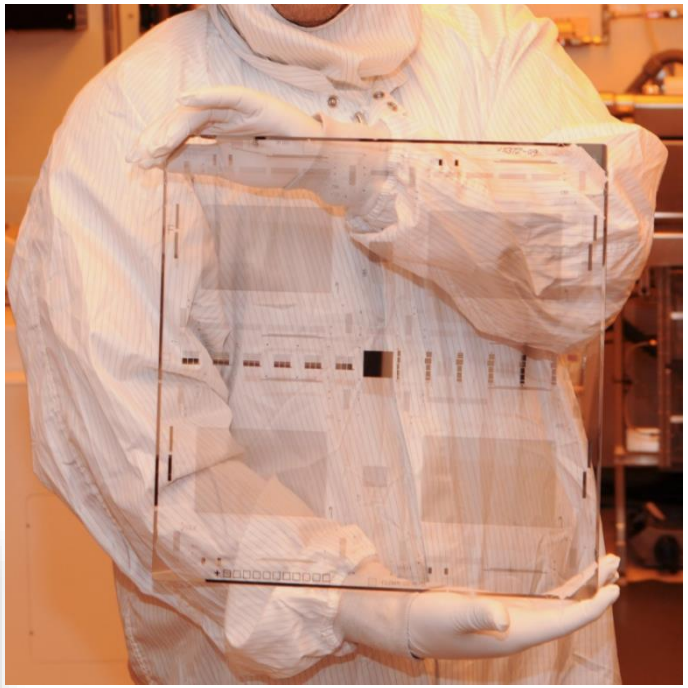
Nature Mater **5**, 33 (2006).

Precise, Deterministic Dispersal of Micro Devices

Stamps with surface relief allow densely packed devices to be dispersed onto non-native substrates in a precise and deterministic manner.

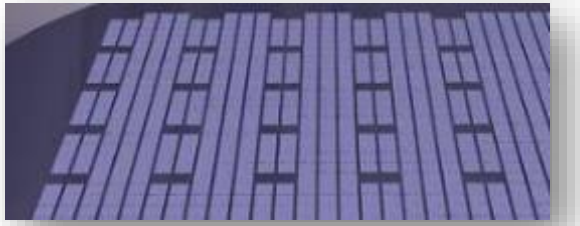






Dispersed micro components

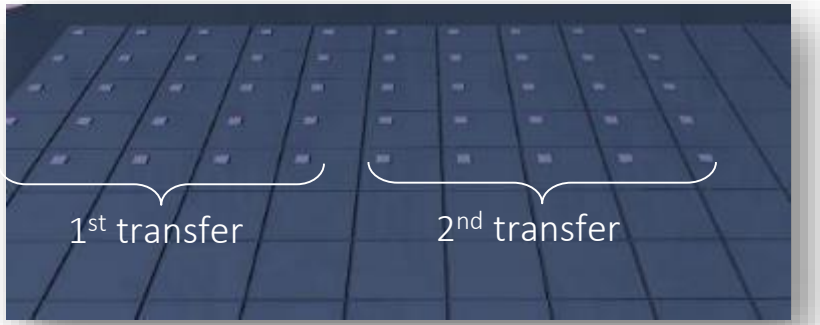
Source Wafer



Densely packed micro components

Printing

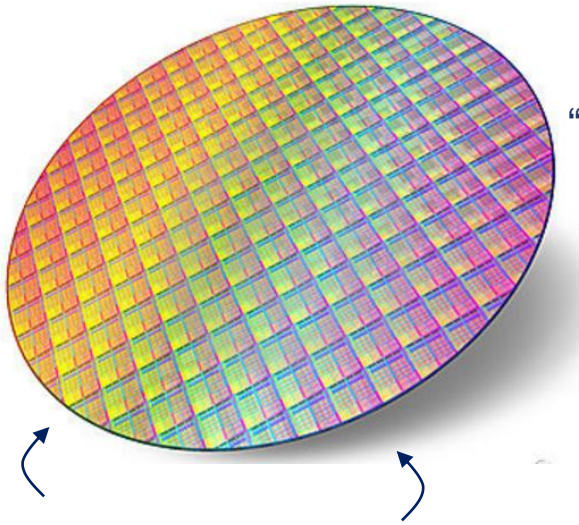
Non-native “Target” Substrate



Dispersed micro components

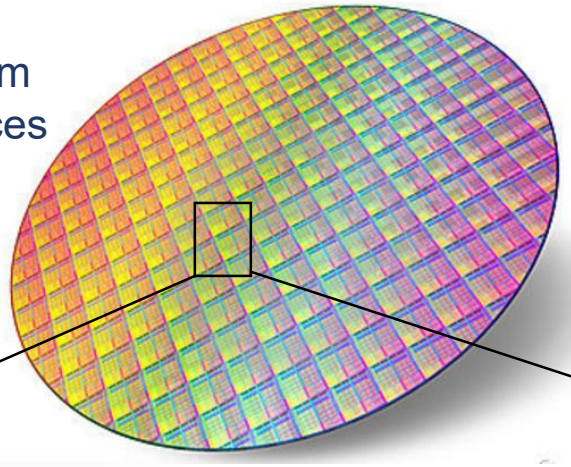
Print-Compatible Micro-devices

Source wafers have print-compatible micro-devices that are undercut and anchored at endpoints using MEMS-like processing strategies.



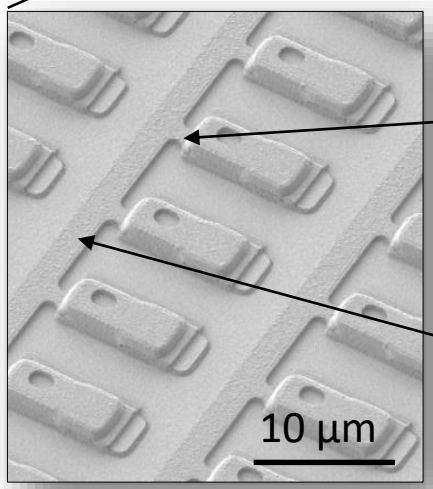
source wafer with devices

Processing to form "print-ready" devices

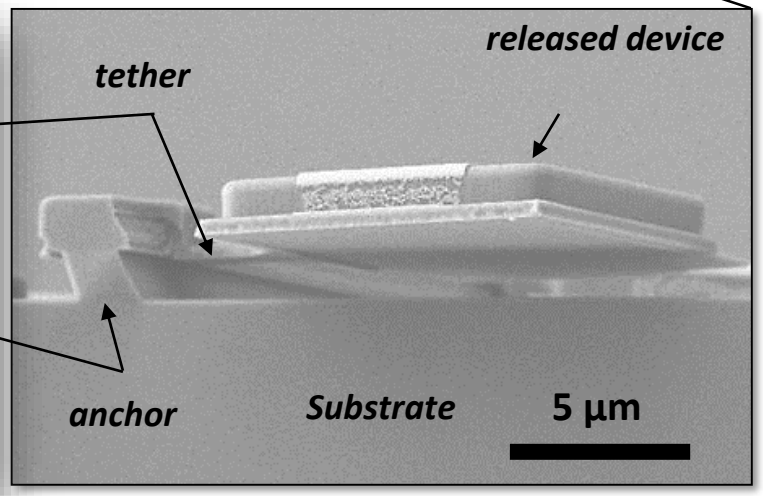


<u>Proven micro-device systems:</u>

Silicon CMOS
Indium Phosphide
Gallium Arsenide
Gallium Nitride
Aluminum Nitride
Dielectrics
& more



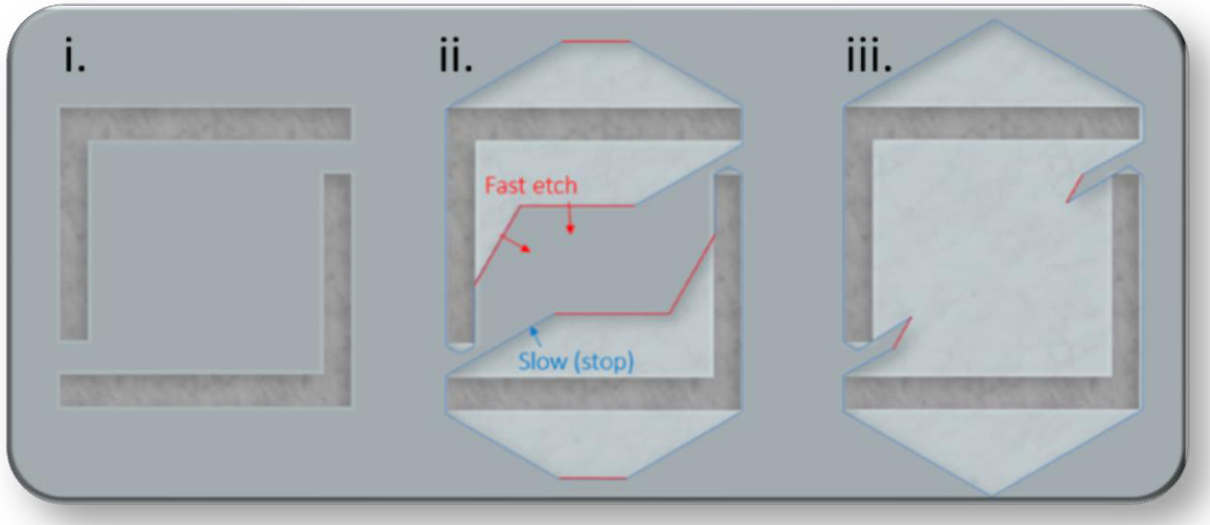
Wafer Top view

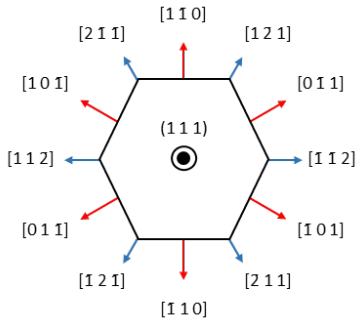


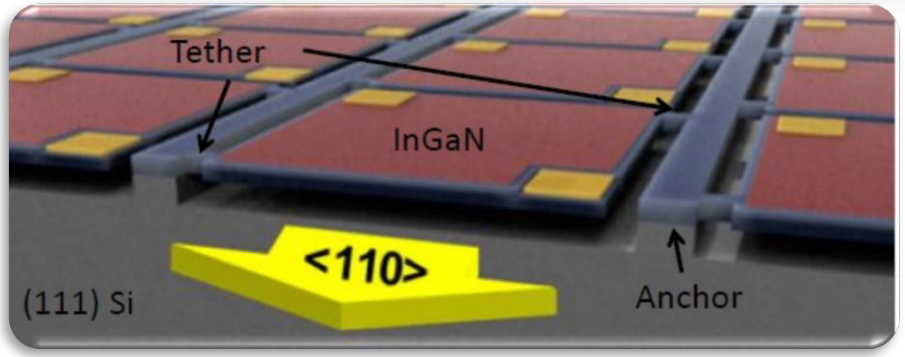
Cleaved source wafer cross-section.

Crystalline Release Layers

Anisotropic etching of Si (1 1 1) by hot aqueous bases:

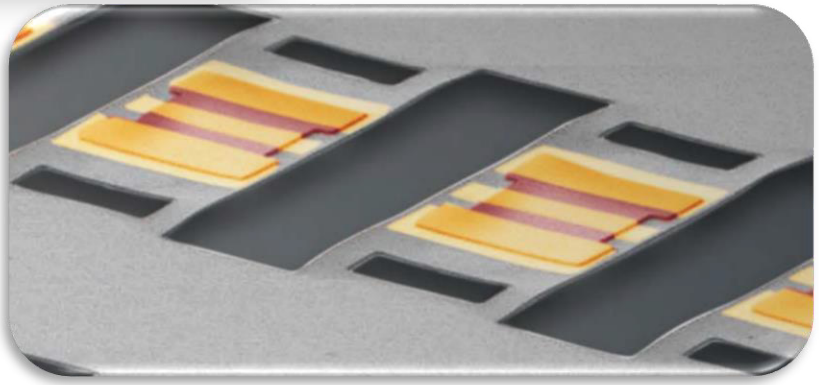






Printable Gallium Nitride LEDs

PNAS **108**, 10072 (2011).

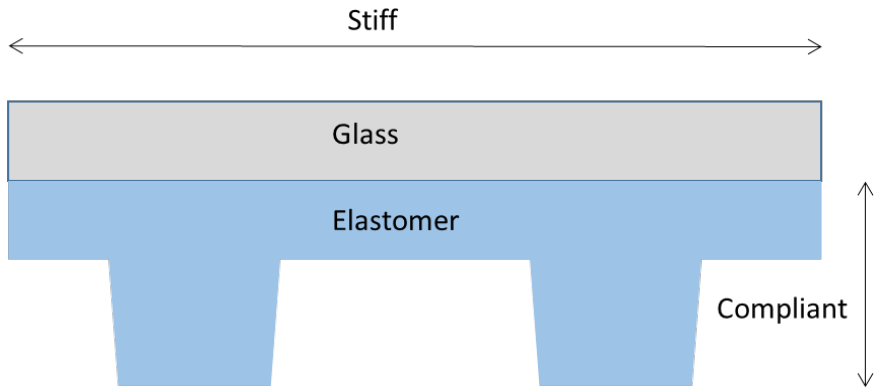


Printable Single Crystal Silicon FETs

Adv. Funct. Mater. **2011**, *21*, 3029–3036

The Elastomer Stamp

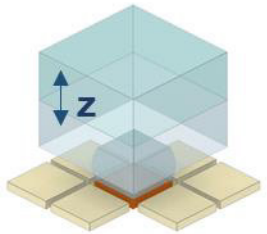
Low-pressure injection molded silicone rubber on glass backing, with lithographically-defined “posts” for selective transfer.



The stamp is…

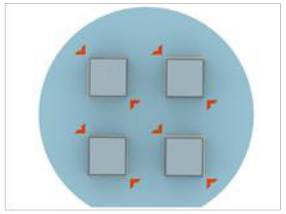
i. …compliant in z…

→ high transfer yield.



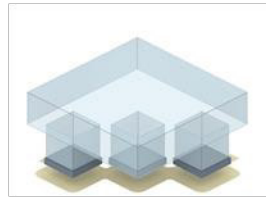
ii. …transparent…

→ high-accuracy placement.

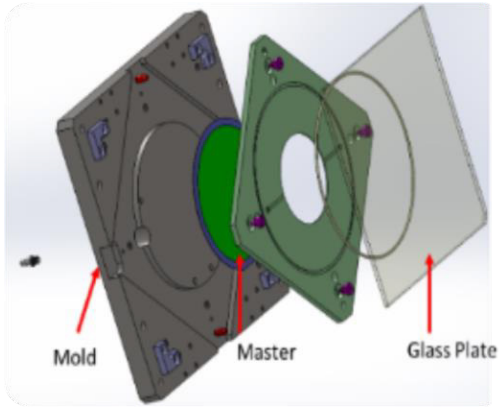


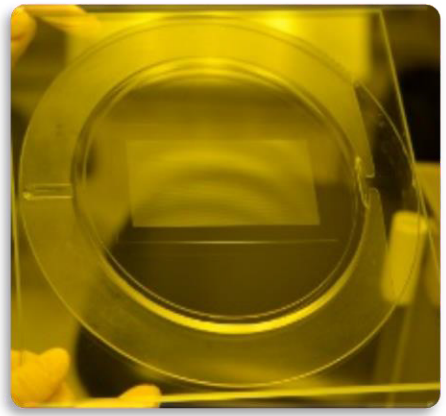
iii. …simple, inexpensive, high-fidelity construction….

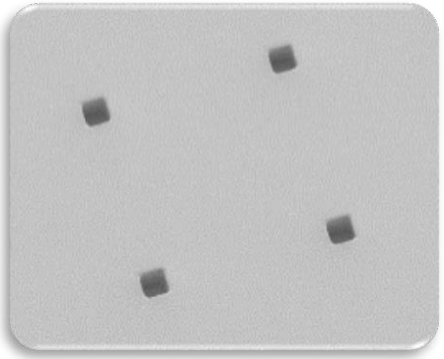
→ scalable, high-throughput

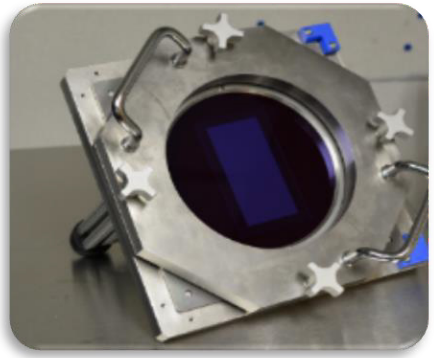


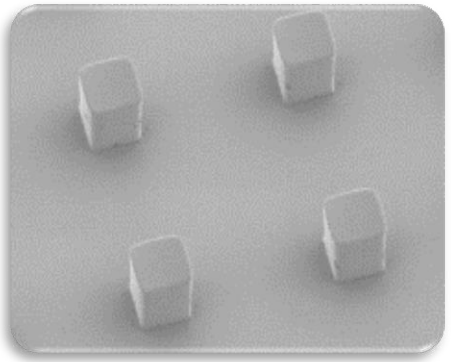
Stamp Fabrication











Silicon Master

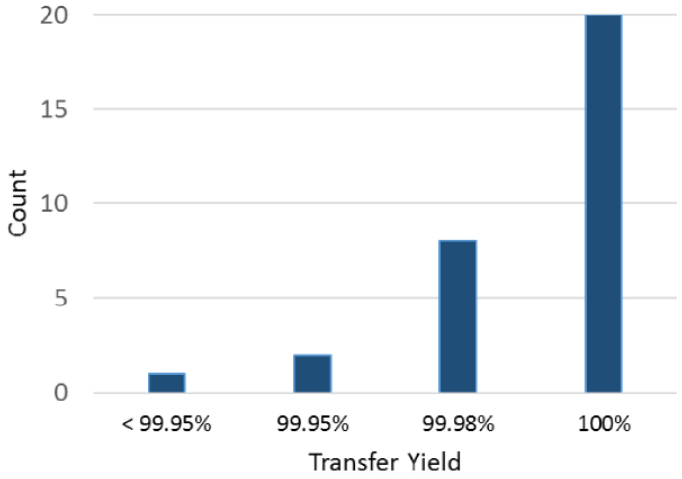
Low-Pressure Injection Molding

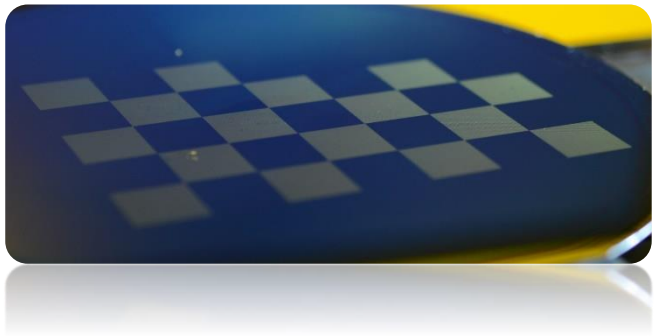
Elastomer Stamp

Elastomer stamp capability demonstrations

i. …compliant (forgiving) in z…

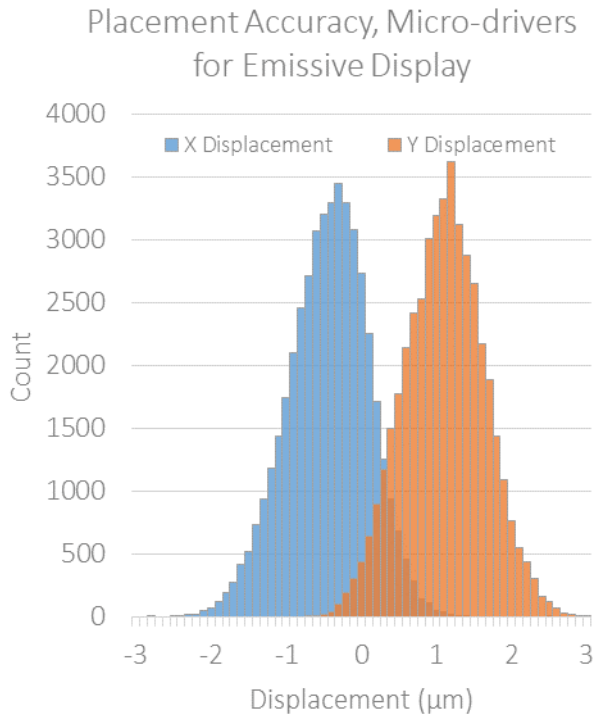
→ high transfer yield.





ii. …transparent

→ high-accuracy placement.

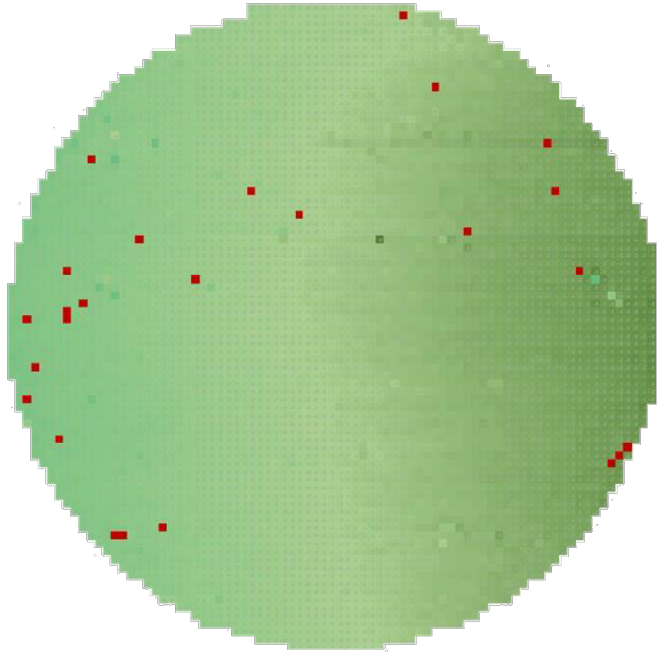


displacement at 3σ: +/- 1.5 µm

iii. …simple, inexpensive, high-fidelity construction….

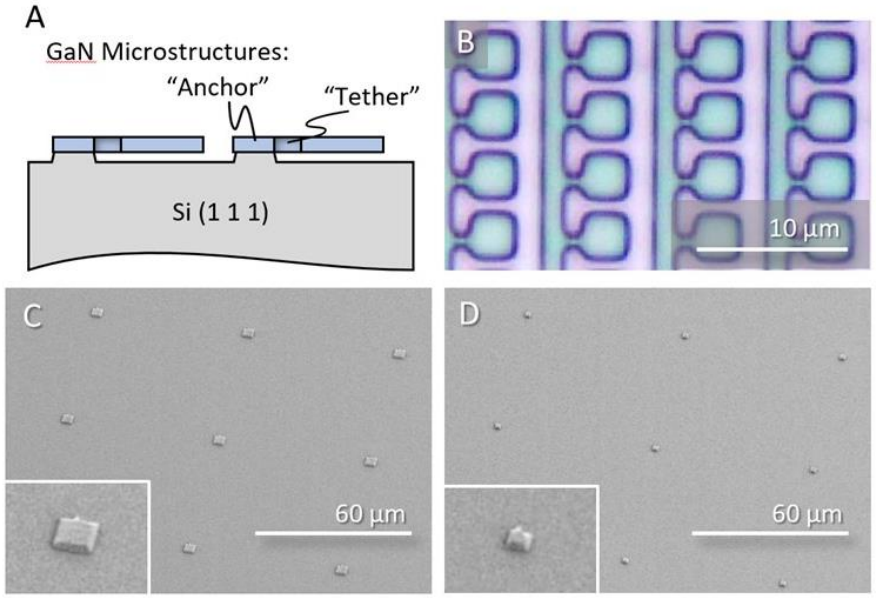
→ scalable, high-throughput

Yield map, 150 mm wafer array transfer:

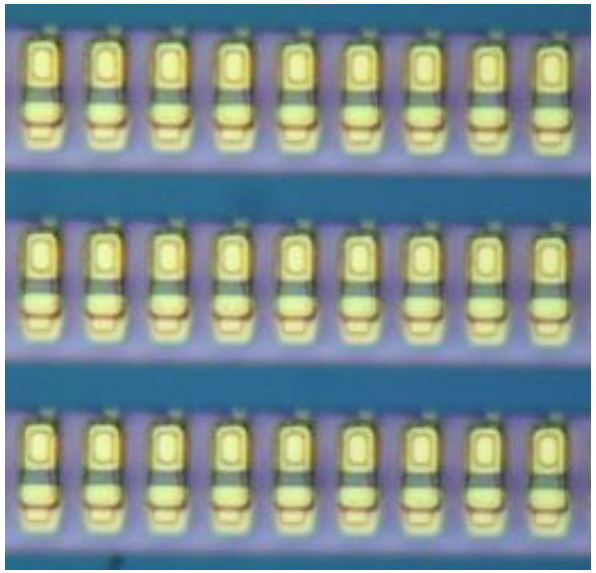


Transferring micron-scale objects with stamp

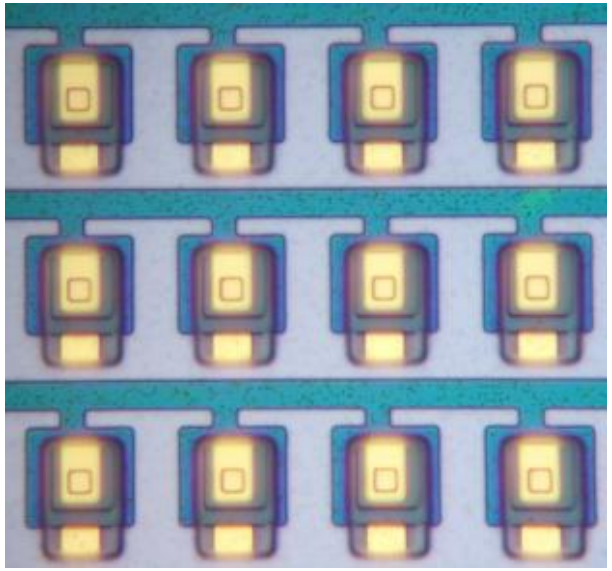
3 µm and 5 µm GaN transferred with stamp:



microLEDs suitable for micro assembly with elastomer stamp:

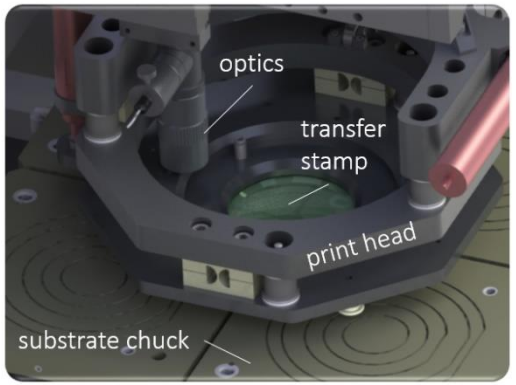


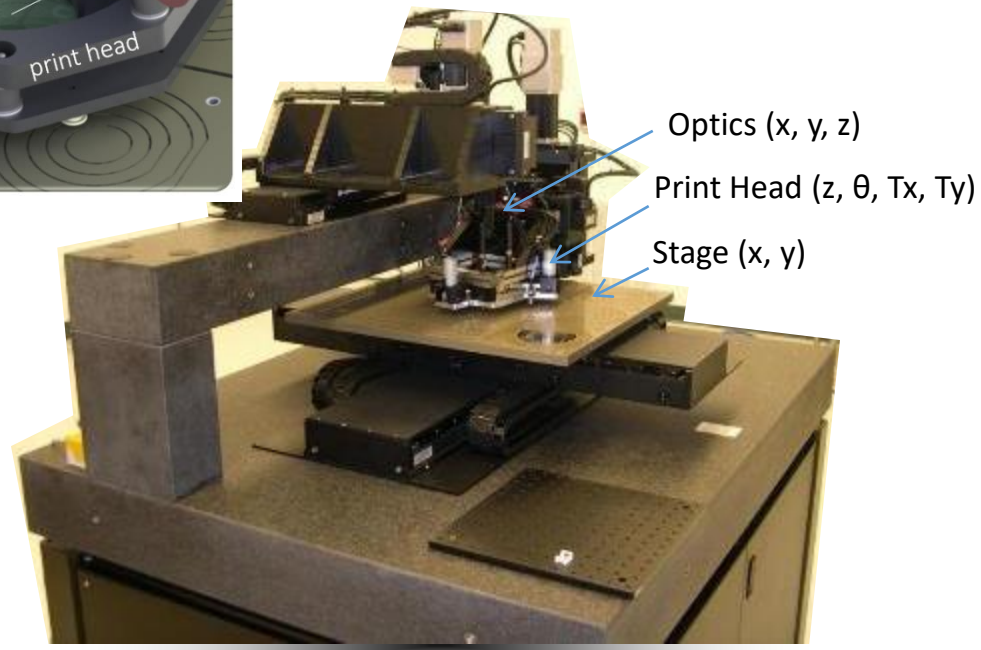
3 x 10 µm^2



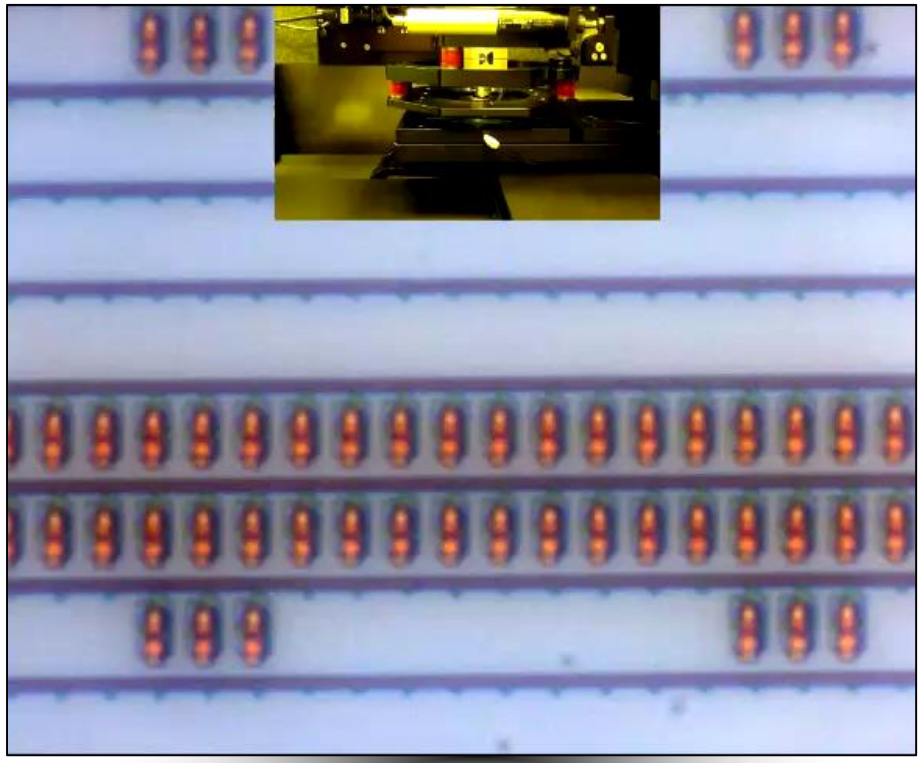
8 x 15 µm^2

Transfer printing MicroLEDs, 10k at a time





stamp + motion + optics



1. *pick-up,*
2. *print,*
3. *clean.*

[repeat]

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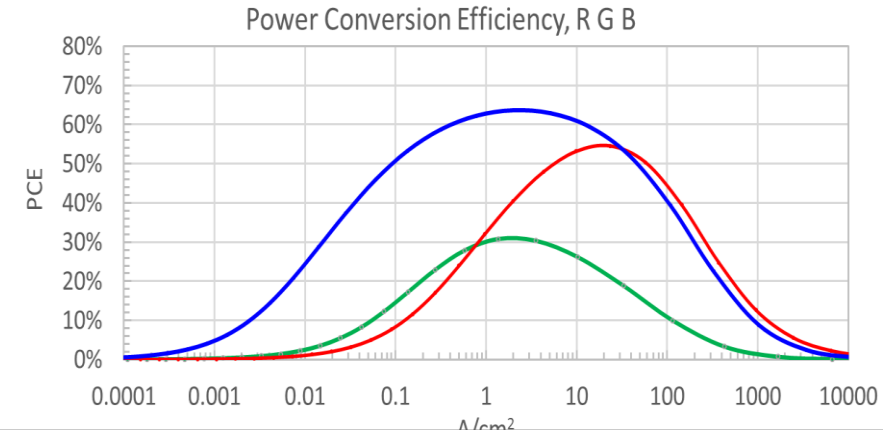
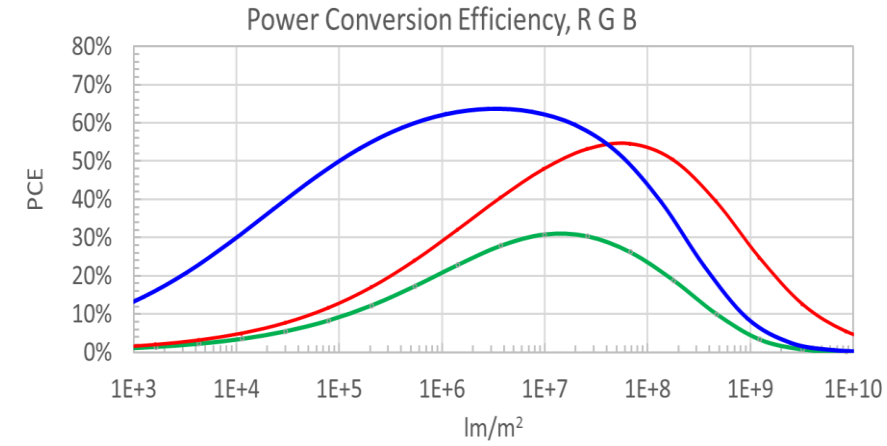
MicroLEDs as self-emitting sub-pixels

Representative behavior of modern LEDs, modeled.



LEDs have highest PCE at current densities ~ 1 to 10 A/cm^2

- non-radiative recombination at low injection
- current crowding & droop at high injection



Designing for display operation at optimal current density:

- ~0.2% pixel area coverage for 5000 nit µILED display
- ~0.02% pixel area coverage for 500 nit µILED display.

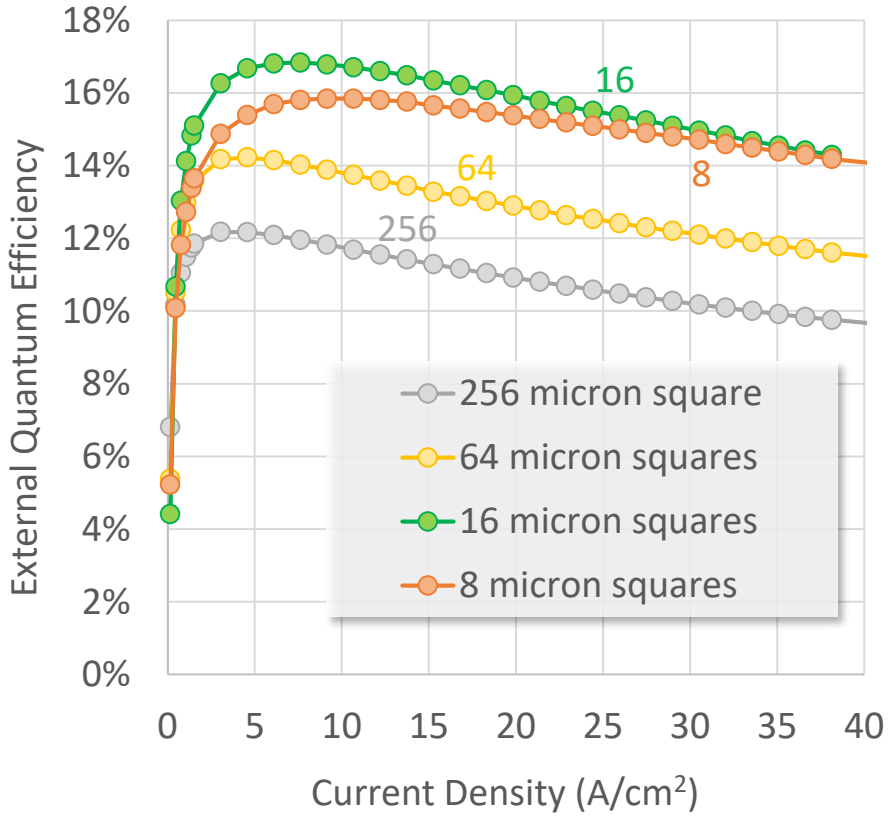
bright, efficient, fast, colorful

+

room to do more

Size Dependent Efficiency, Blue LEDs

- Peak EQE rises as devices miniaturize from 256 to 16 µm.
- Performance improvements likely with optimized designs, materials, etches, and passivation.

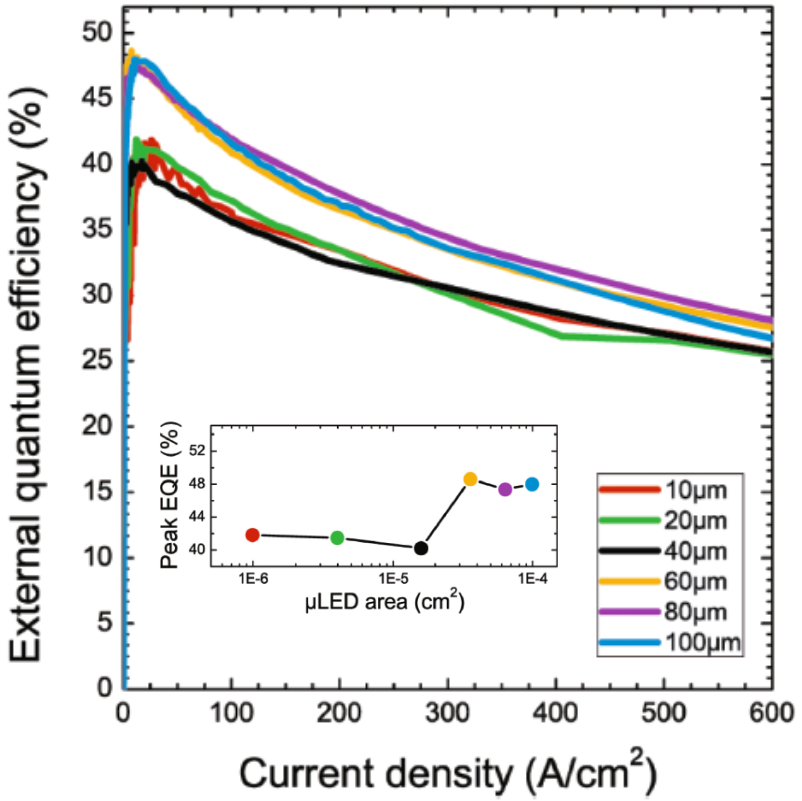


SPIE OPTO 2017

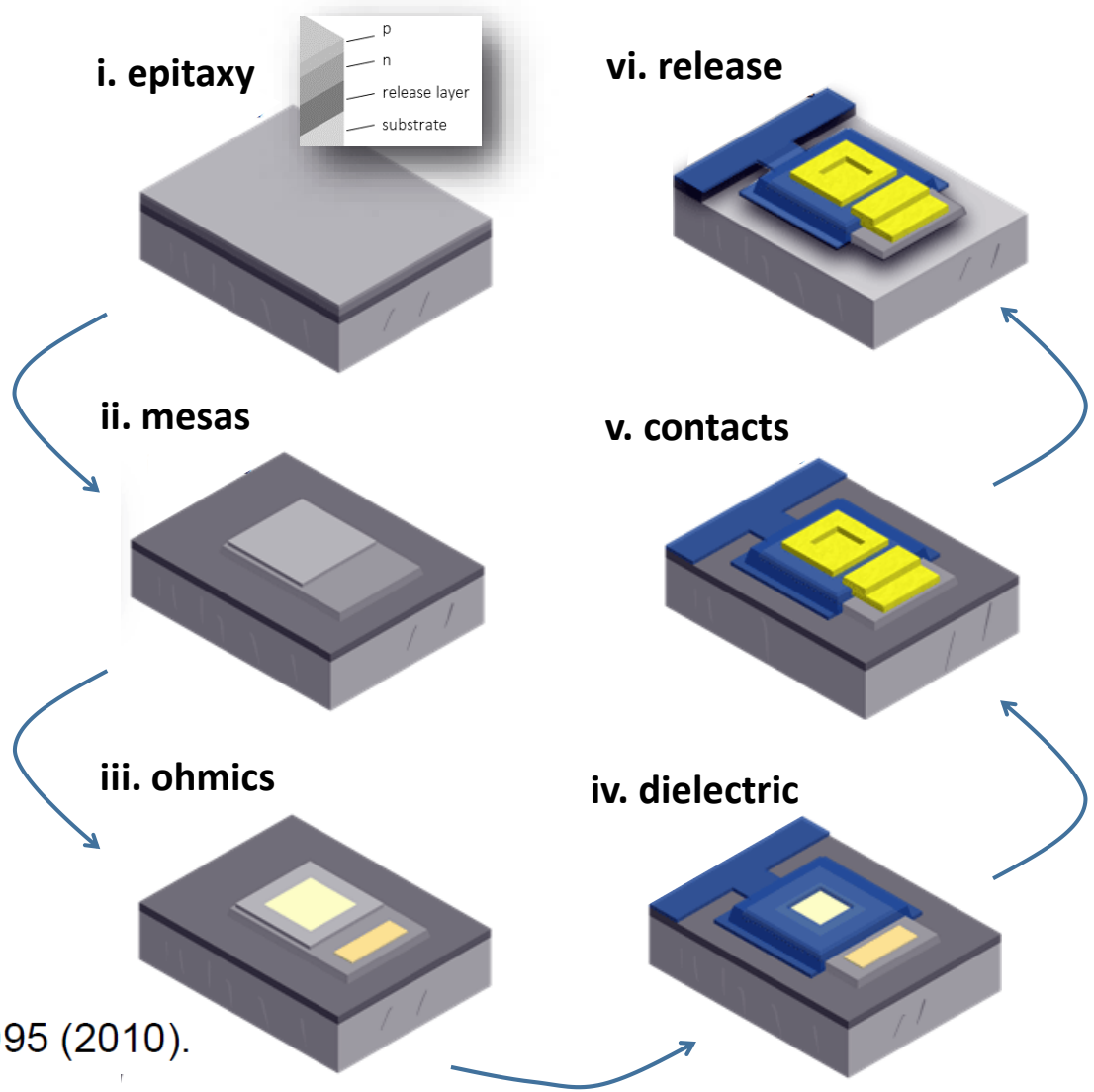
Applied Physics Express **10**, 032101 (2017)
https://doi.org/**10.7567/APEX.10.032101**

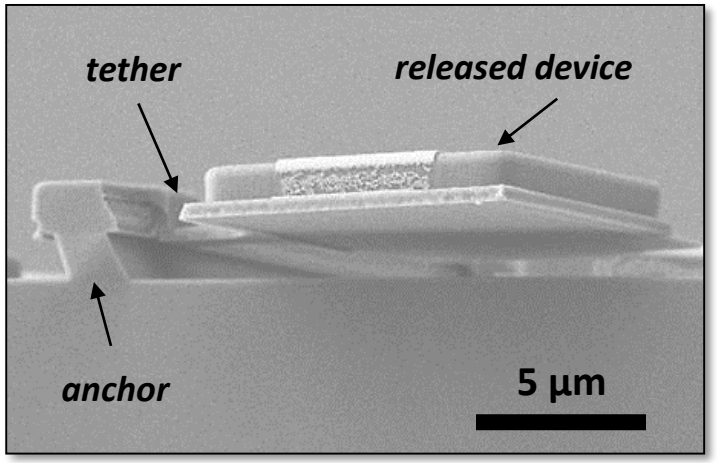
Sustained high external quantum efficiency in ultrasmall blue III–nitride micro-LEDs

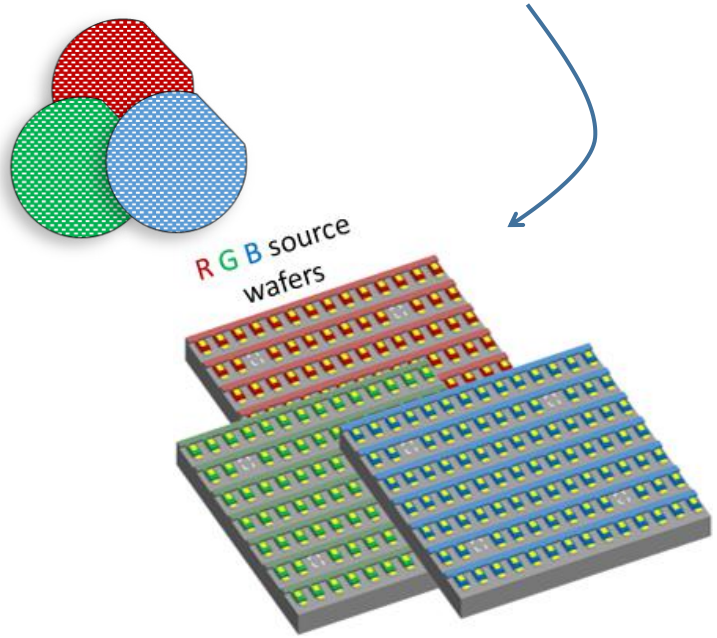
David Hwang[1*], Asad Mughal[1], Christopher D. Pynn[1], Shuji Nakamura[1,2], and Steven P. DenBaars[1,2]



MicroLED Fabrication Sequence



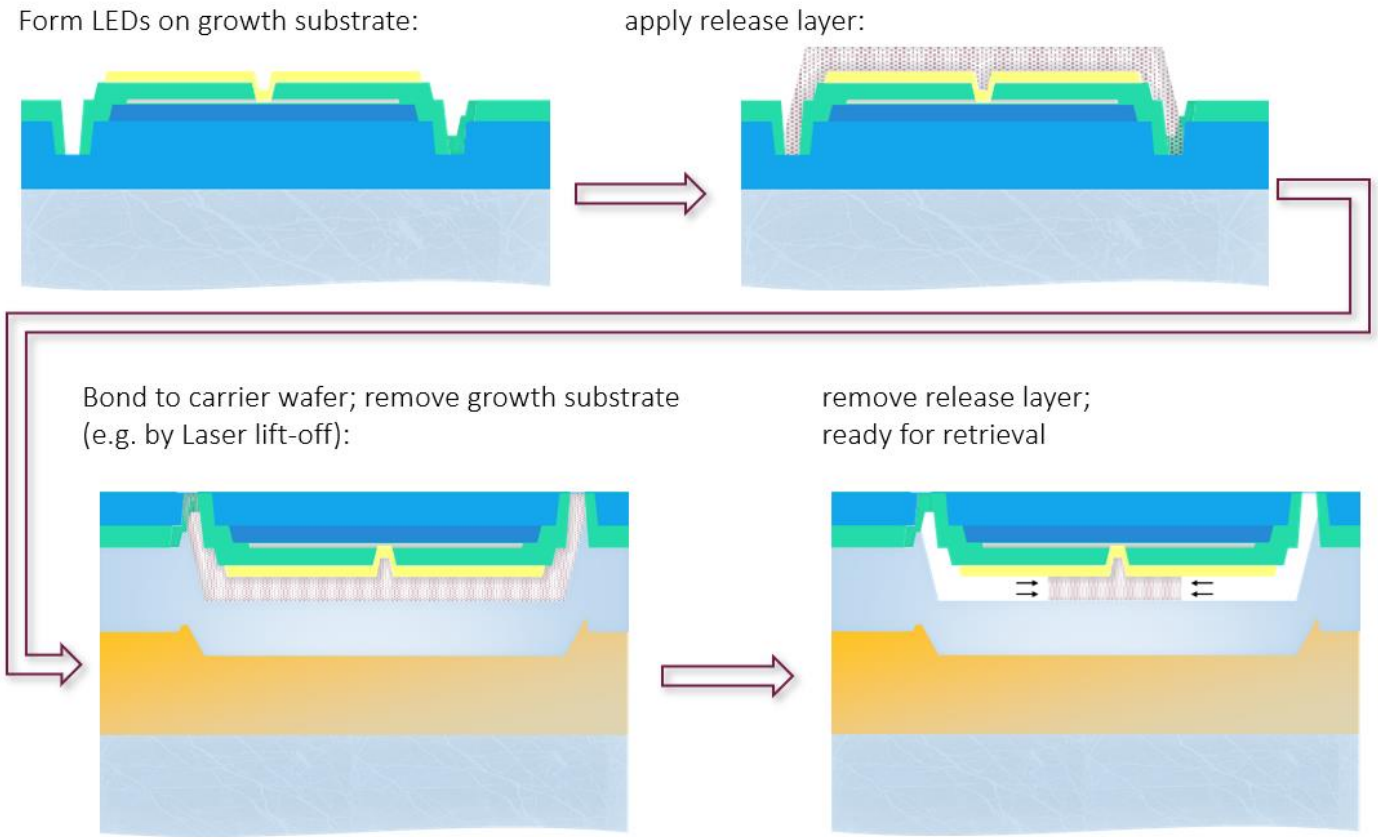


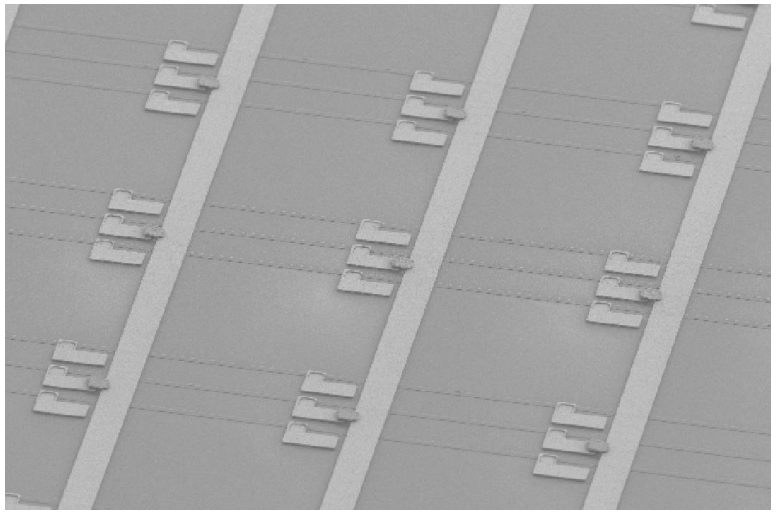


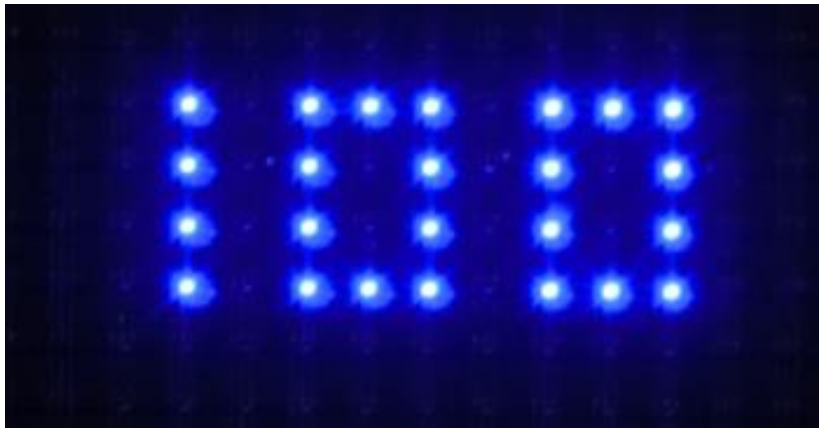
PNAS **107**, 17095 (2010).

SID 2016 DIGEST

Printable MicroLEDs from Sapphire







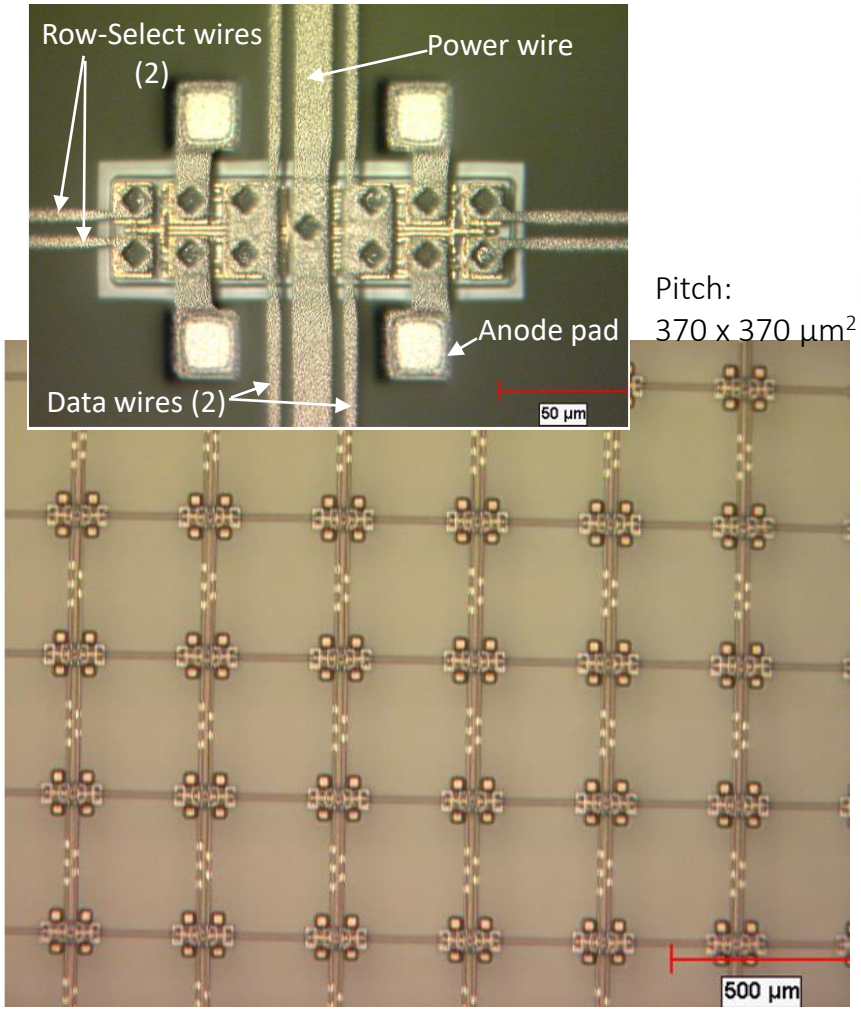
SID 2017 DIGEST

Making microLED Displays

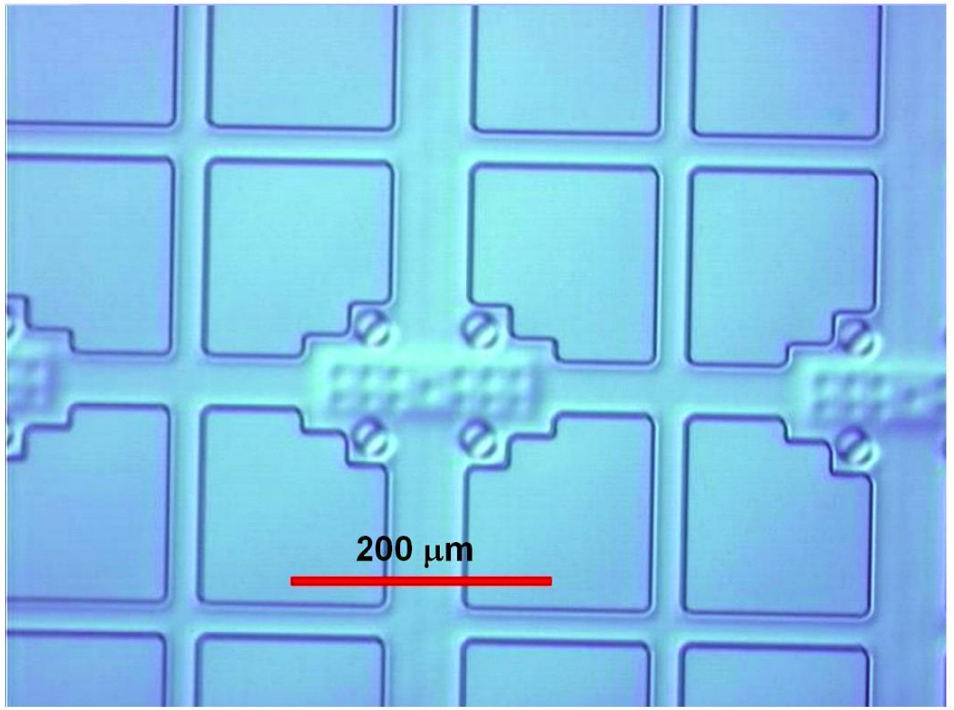
Mass transfer with elastomer stamps for microLED displays.

1. Introduction
2. Micro-Transfer Printing
3. MicroLEDs & Displays
4. **Examples of Printed Displays**
5. Manufacturing Strategies

Early Microdriver/µ-IC AMOLED Results



Pitch:
370 x 370 µm^2



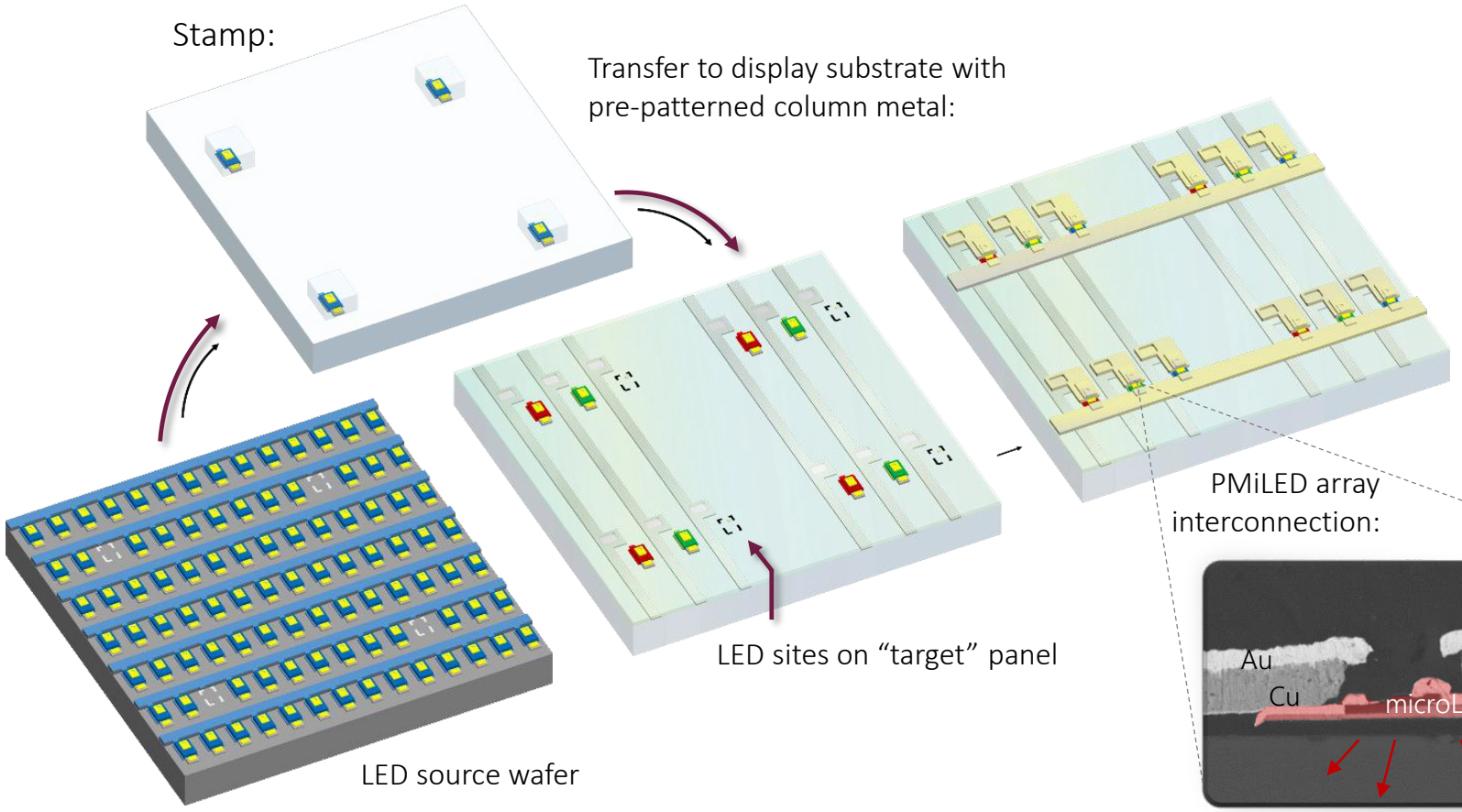
November, 2008

SID 2009 DIGEST
Semprius & Kodak

Passive matrix microLED by printing

Stamp:

Transfer to display substrate with pre-patterned column metal:



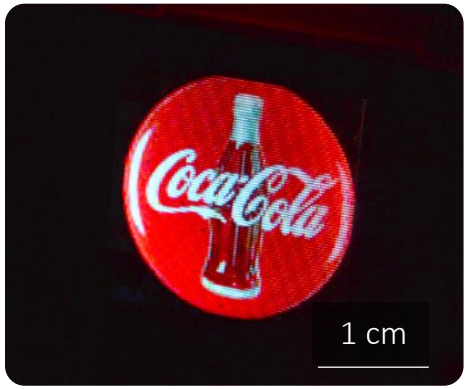
LED source wafer

→ *Different "source" for each color*

LED sites on "target" panel

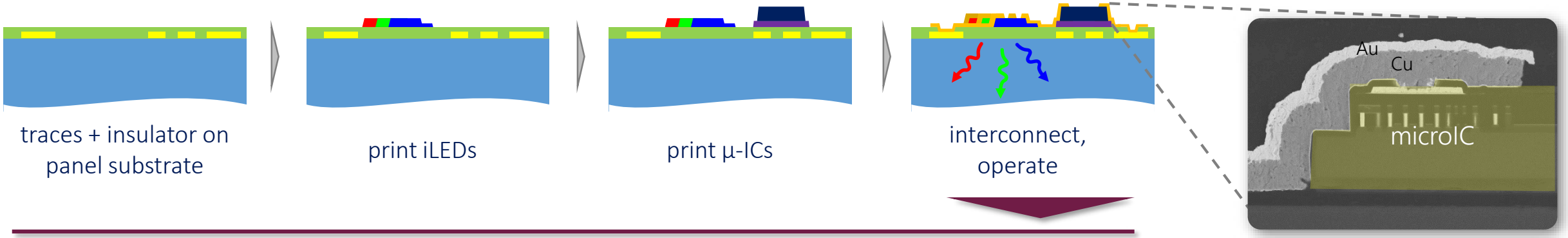
PMiLED array interconnection:

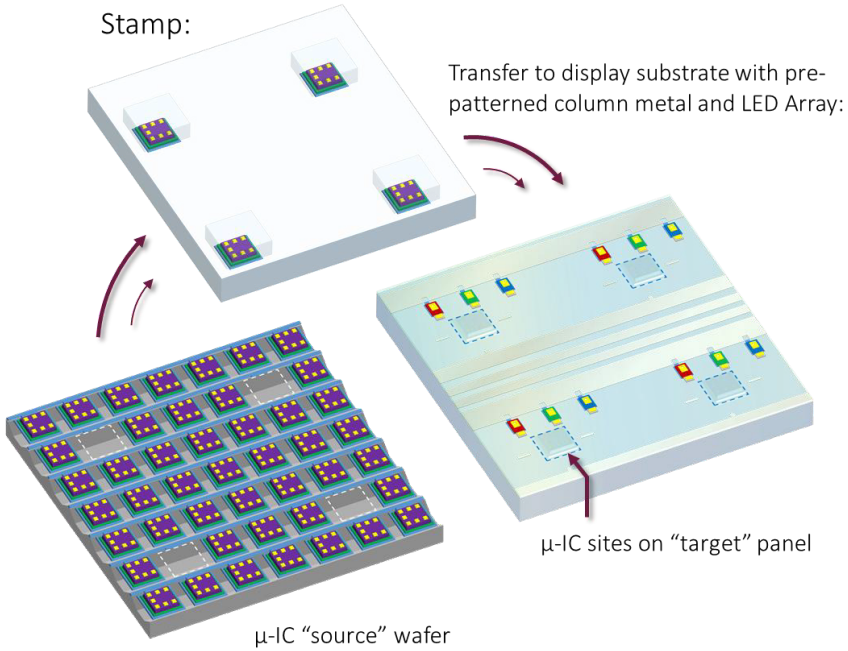
...on glass & plastic:

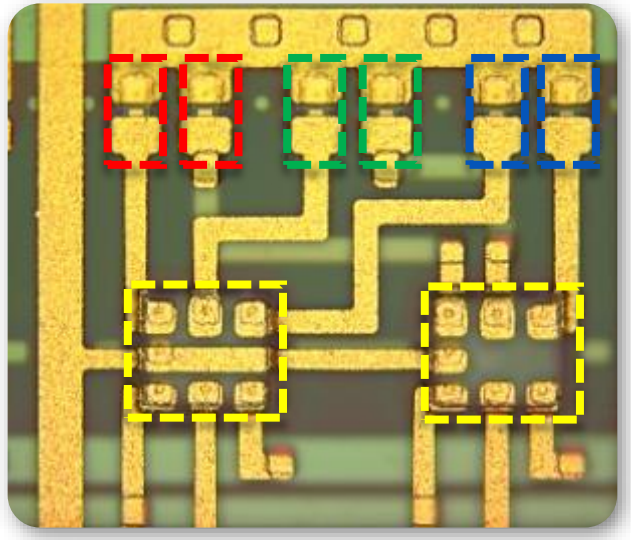


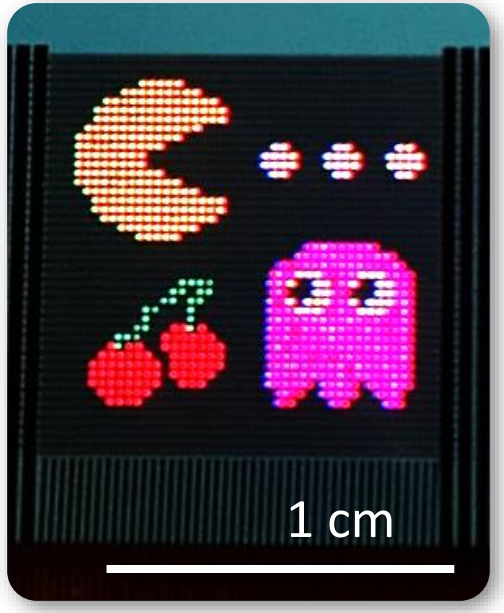
SID 2016 DIGEST

Active matrix microLED





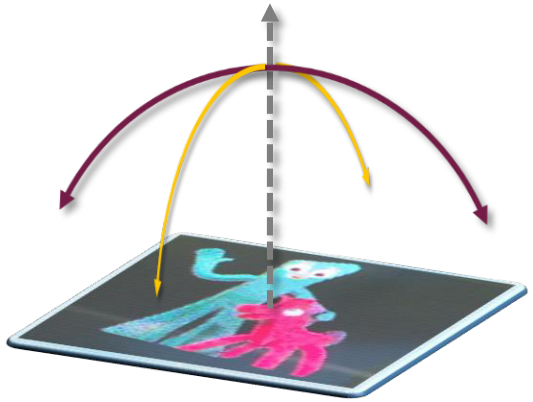


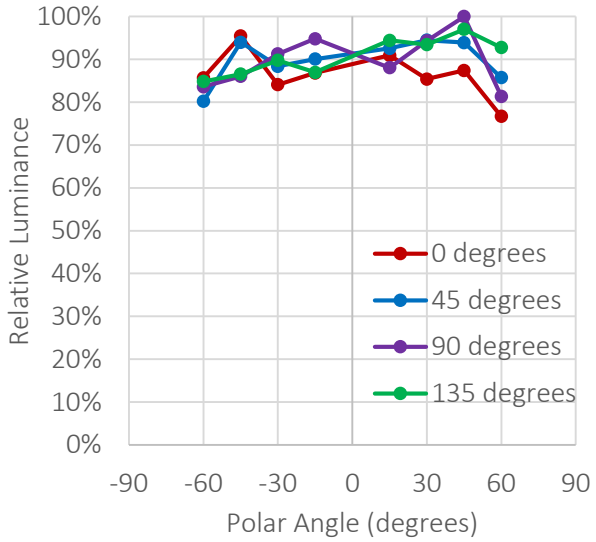


SID 2017 DIGEST

Viewing angle and color

Wide Viewing Angle:

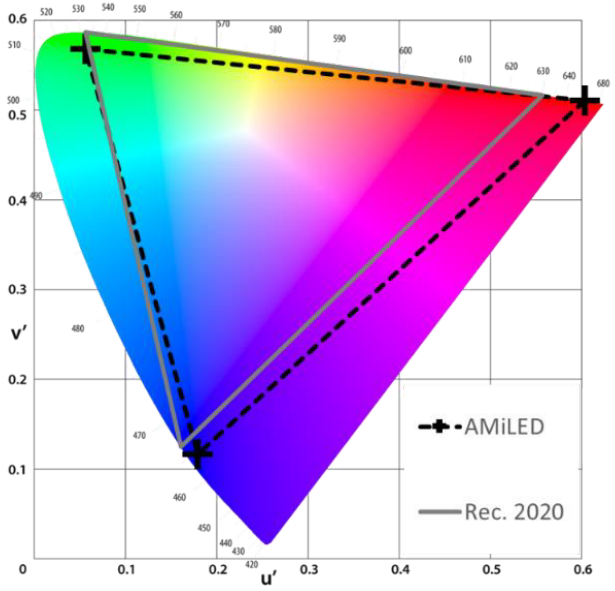


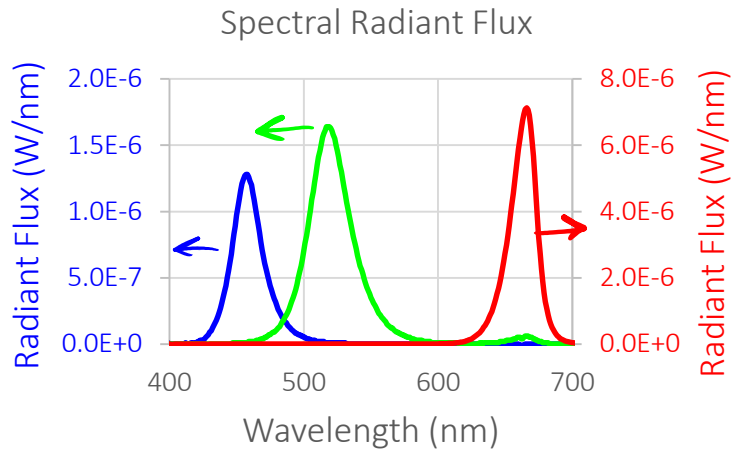


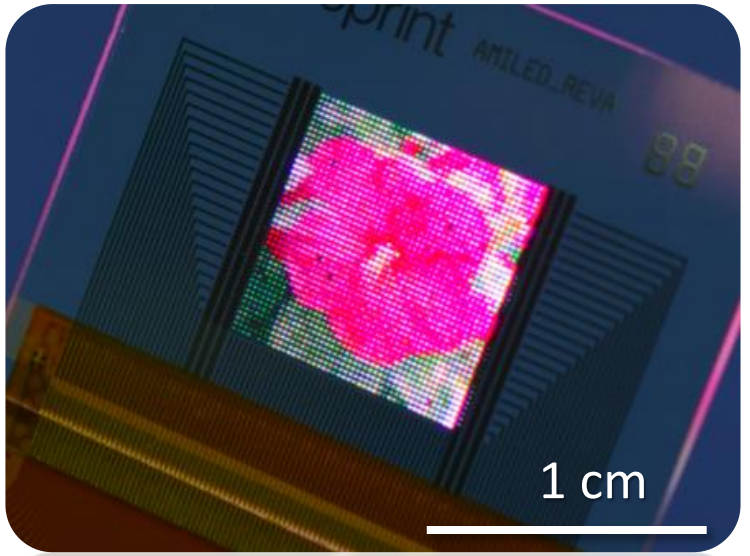
Strong Color Gamut:

Relative to Rec. 2020:

	u' v'	x y
Area	107.1%	90.6%
Overlap	93.3%	84.1%



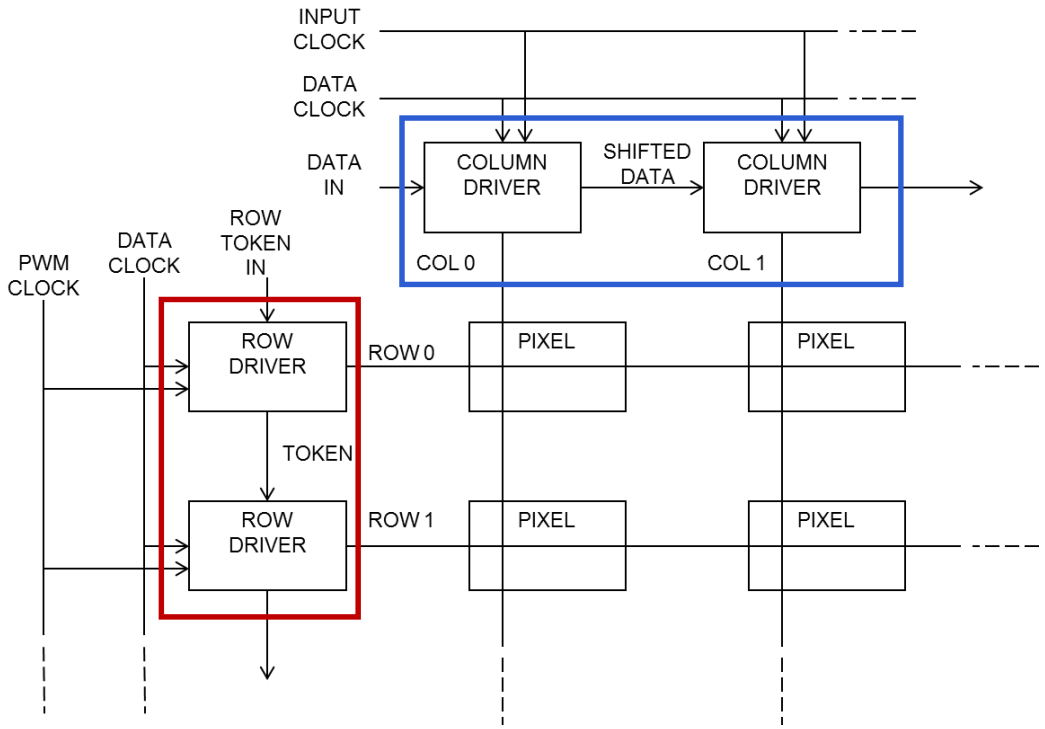




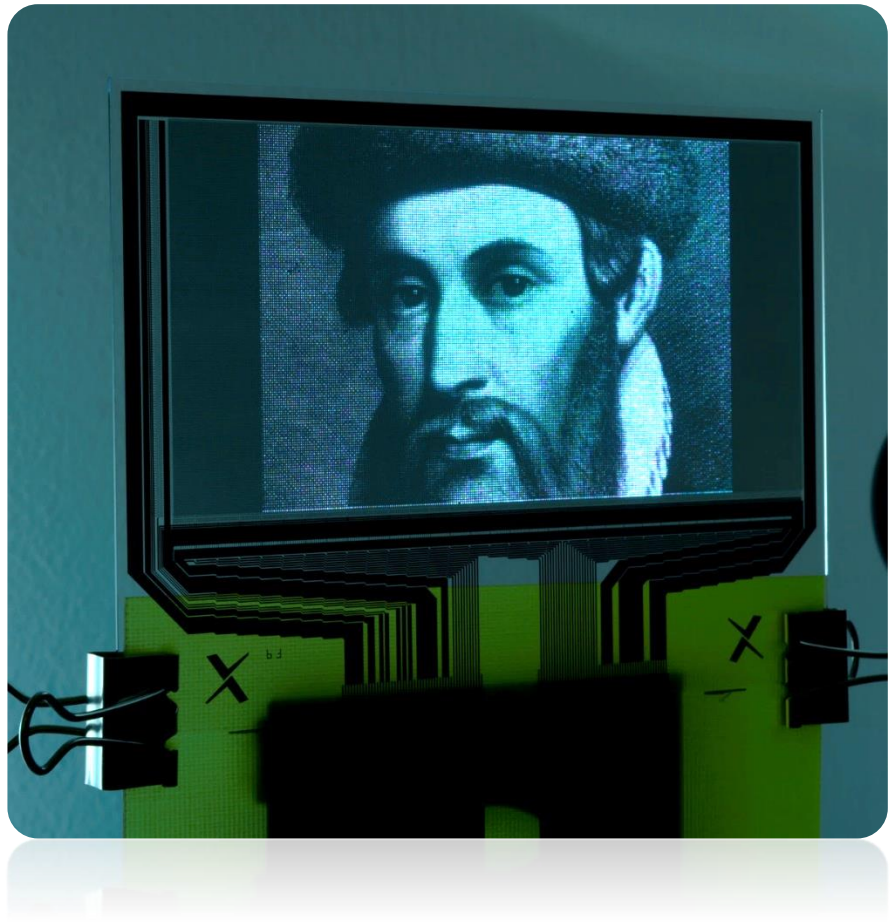
Larger active matrix displays

Print row drivers and column drivers to reduce external I/O count:

- Column drivers demultiplex data
- Row drivers run progressive scan of data load and PWM

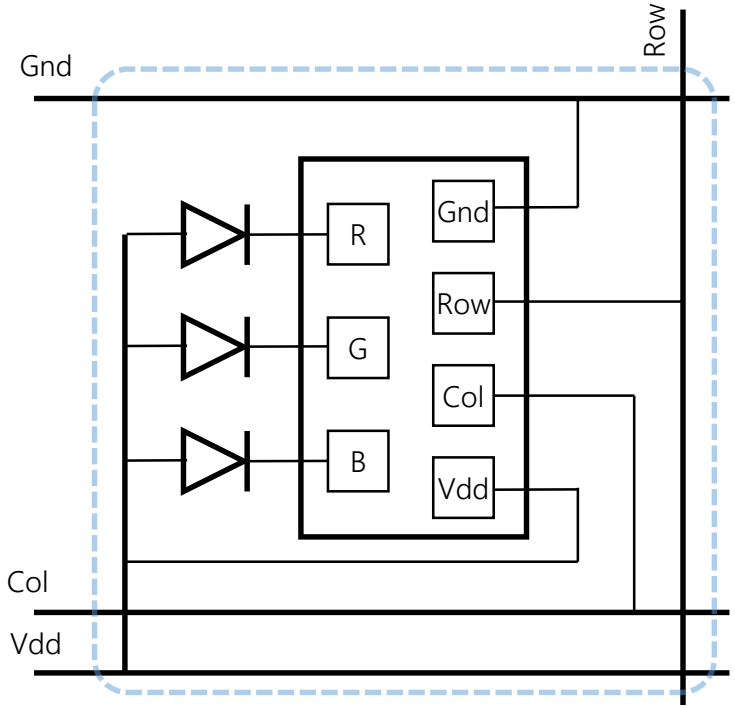


5.1" Diagonal AMILED display 320 x 160, 70 ppi:

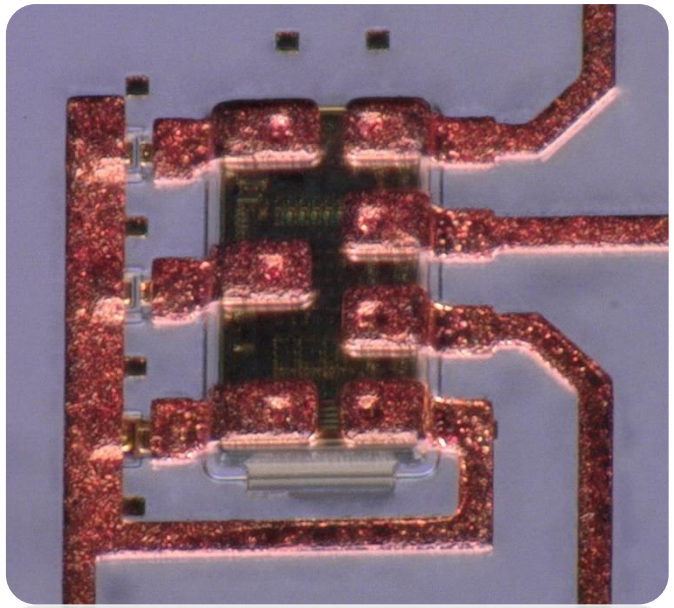


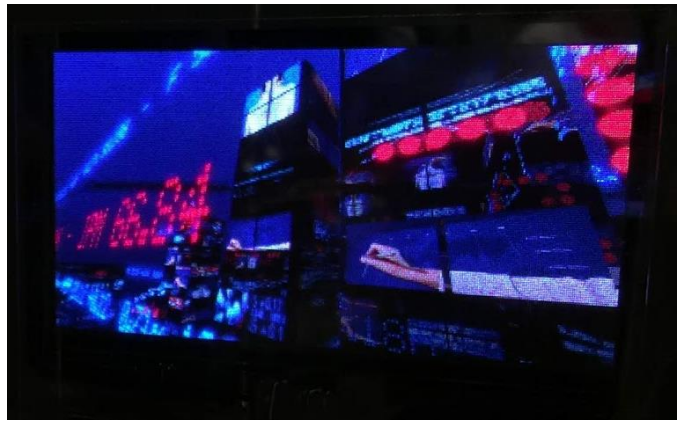
320 x 160 AMILED, 70 ppi

Row, column, power, and ground into each pixel:

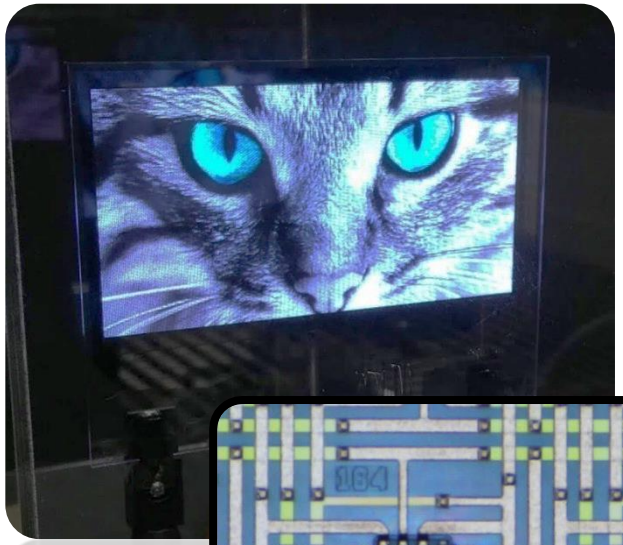


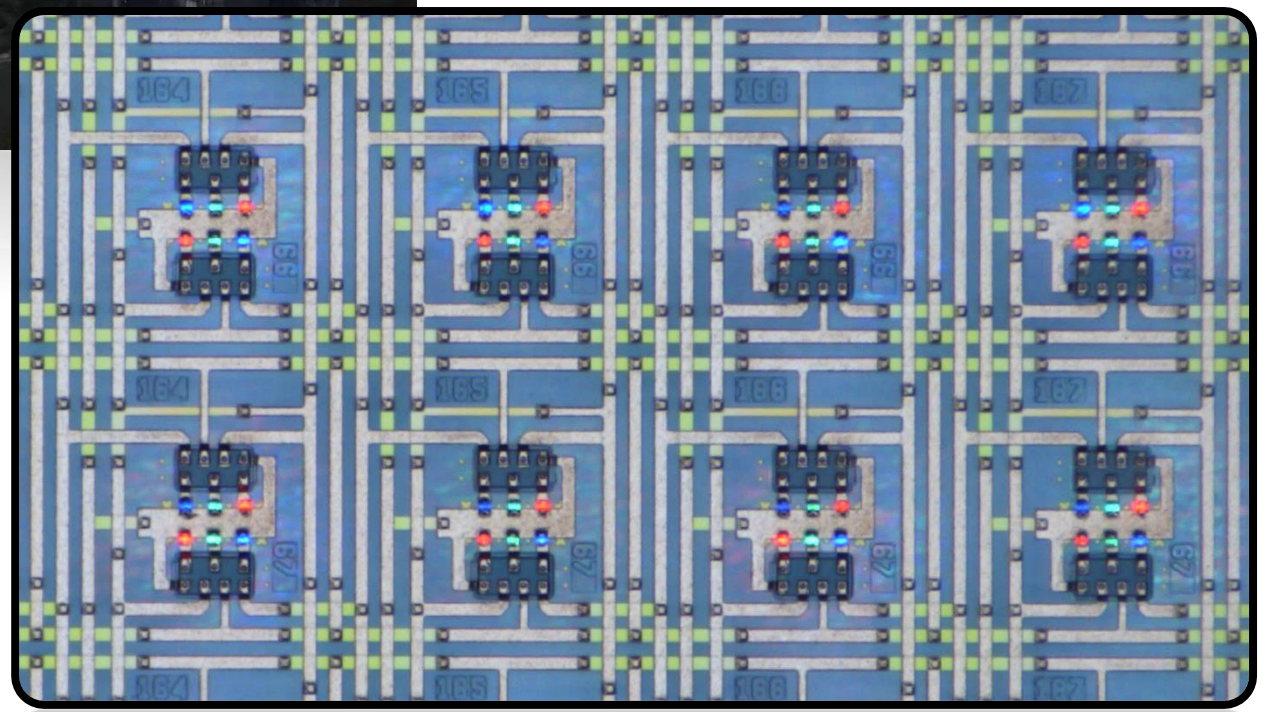
Cu redistribution layer interconnects microLEDs, ICs, and row/col drivers (not shown).





Functional Yield of Sub-Pixels in 5.1″ display





Implementation of redundancy in microICs, microLEDs, row & column lines.

Remaining yield impactors:

- Forward voltage of LEDs
- Metallization defects (laser cut)
- Transfer (typ. < 3 sub-pixels)

Red: 99.98% (9 dark)

Green: 99.95% (28 dark)

Blue: 99.95% (24 dark)

Making microLED Displays

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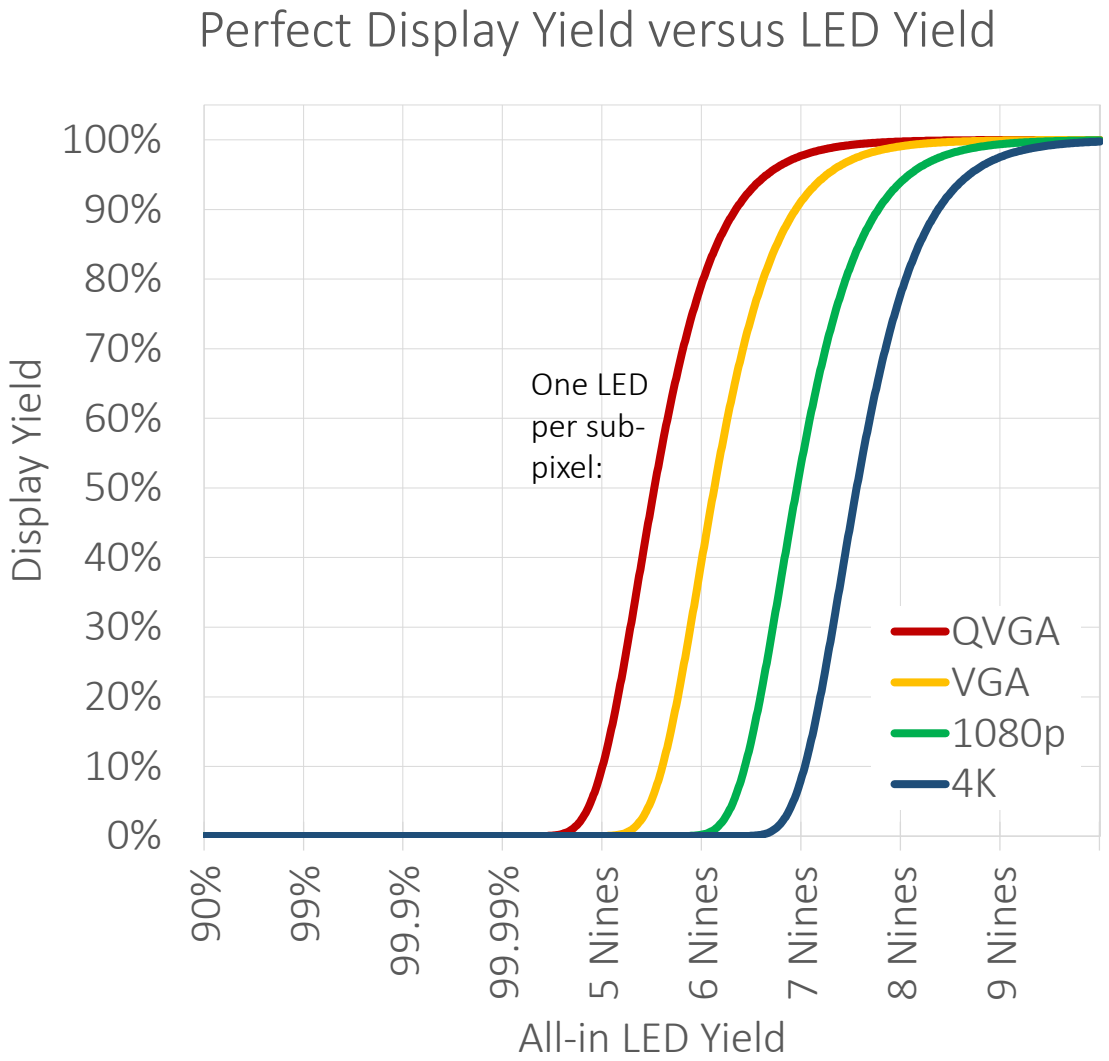
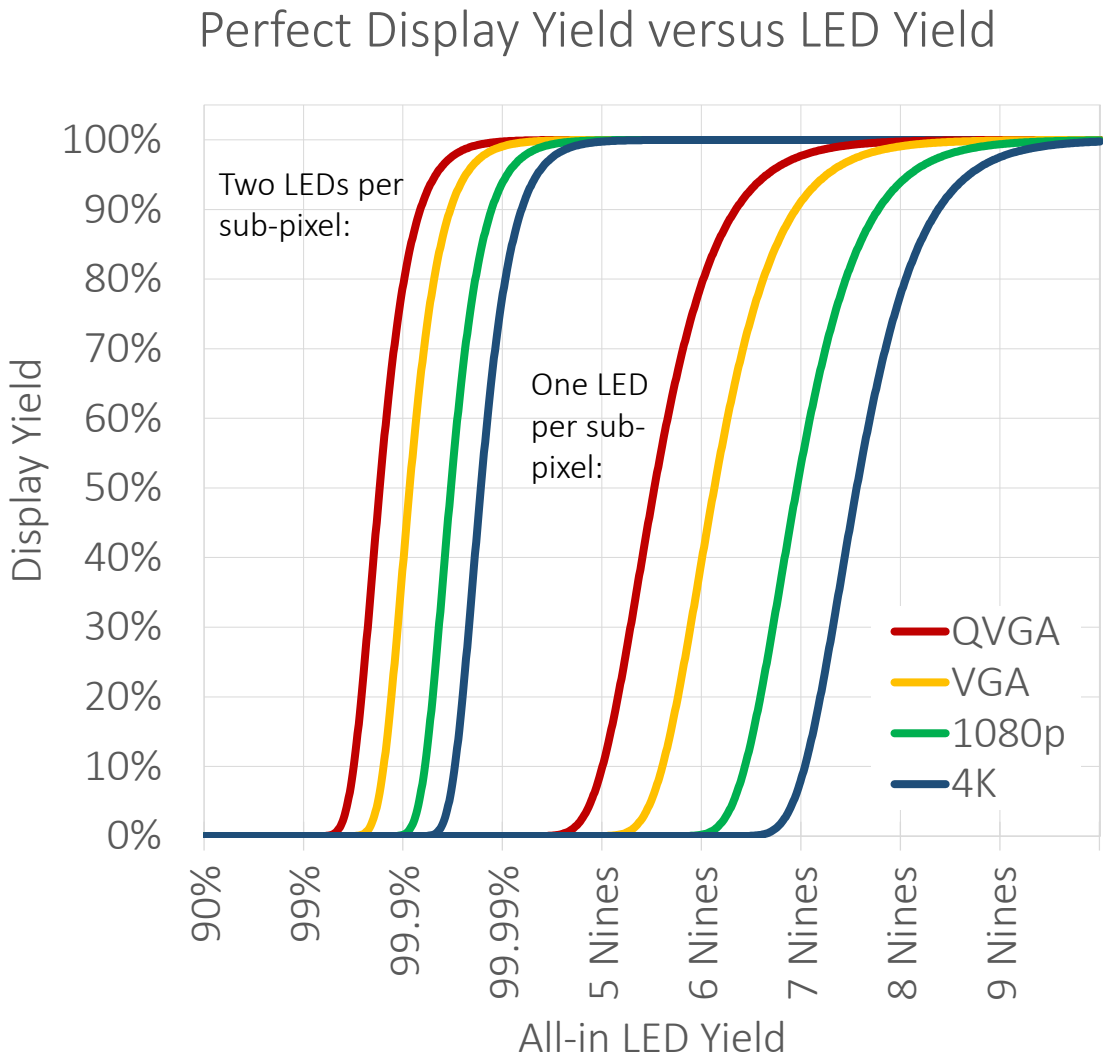
Yielding Perfect Displays



Avenues:

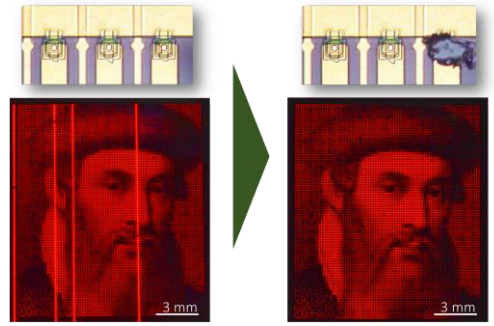
1. Excellent first-pass yield

Yielding Perfect Displays

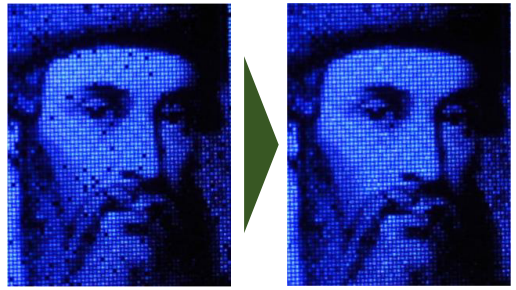


Avenues:

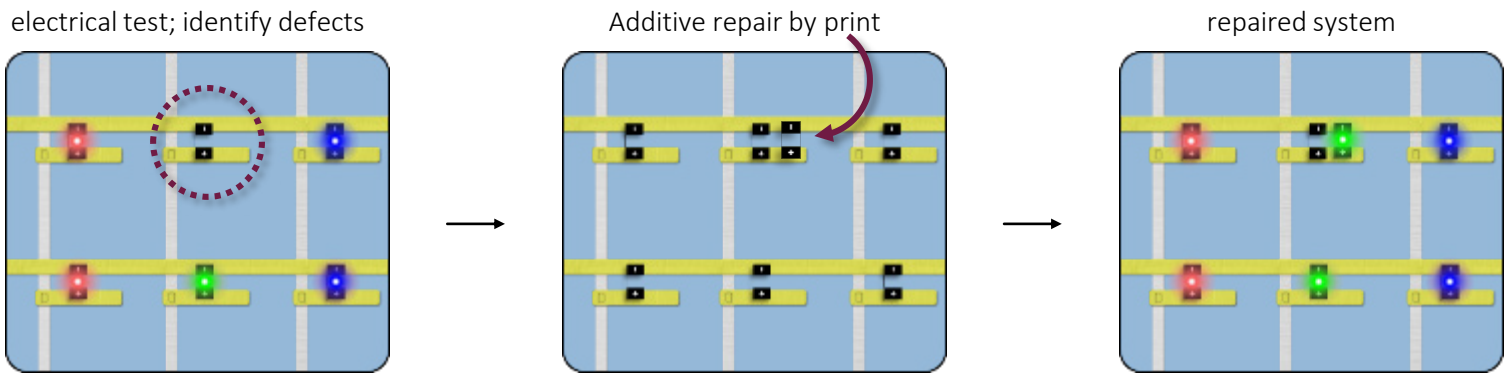
1. Excellent first-pass yield
2. Physical Repair

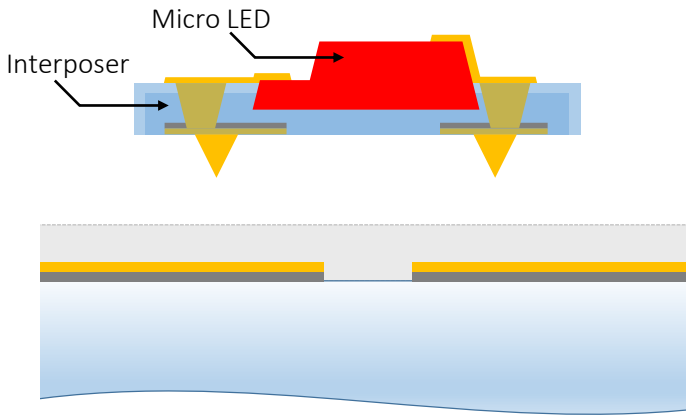


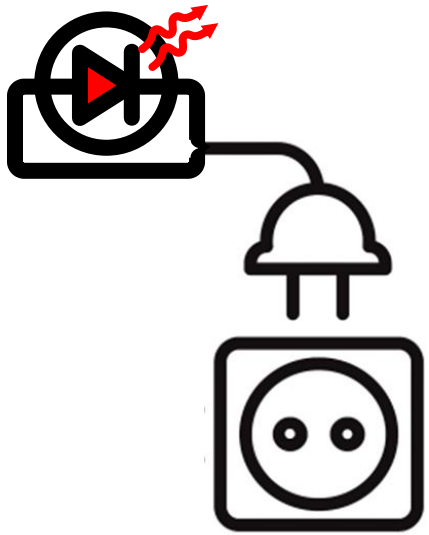
3. Redundancy



System Test and Repair by Interconnection During the Print Operation

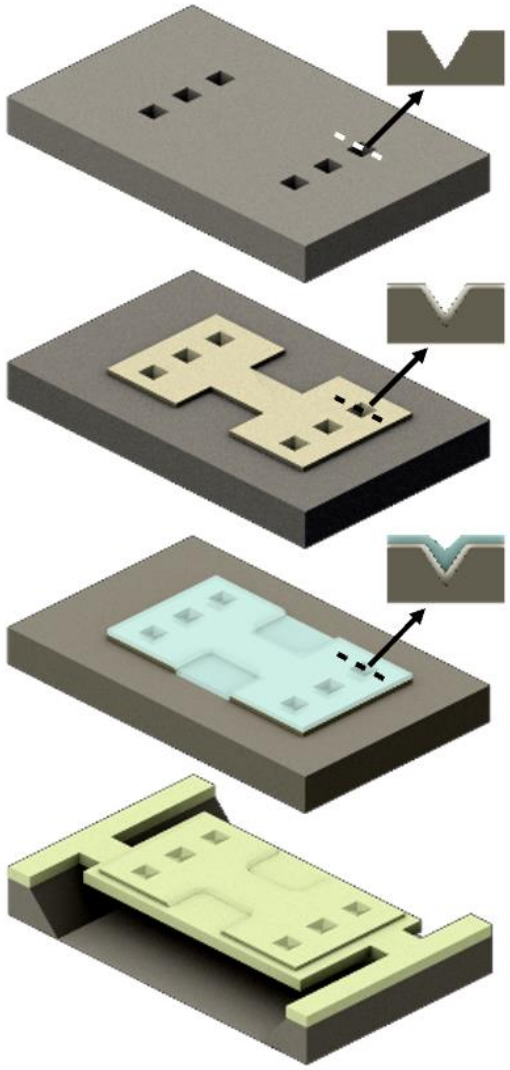


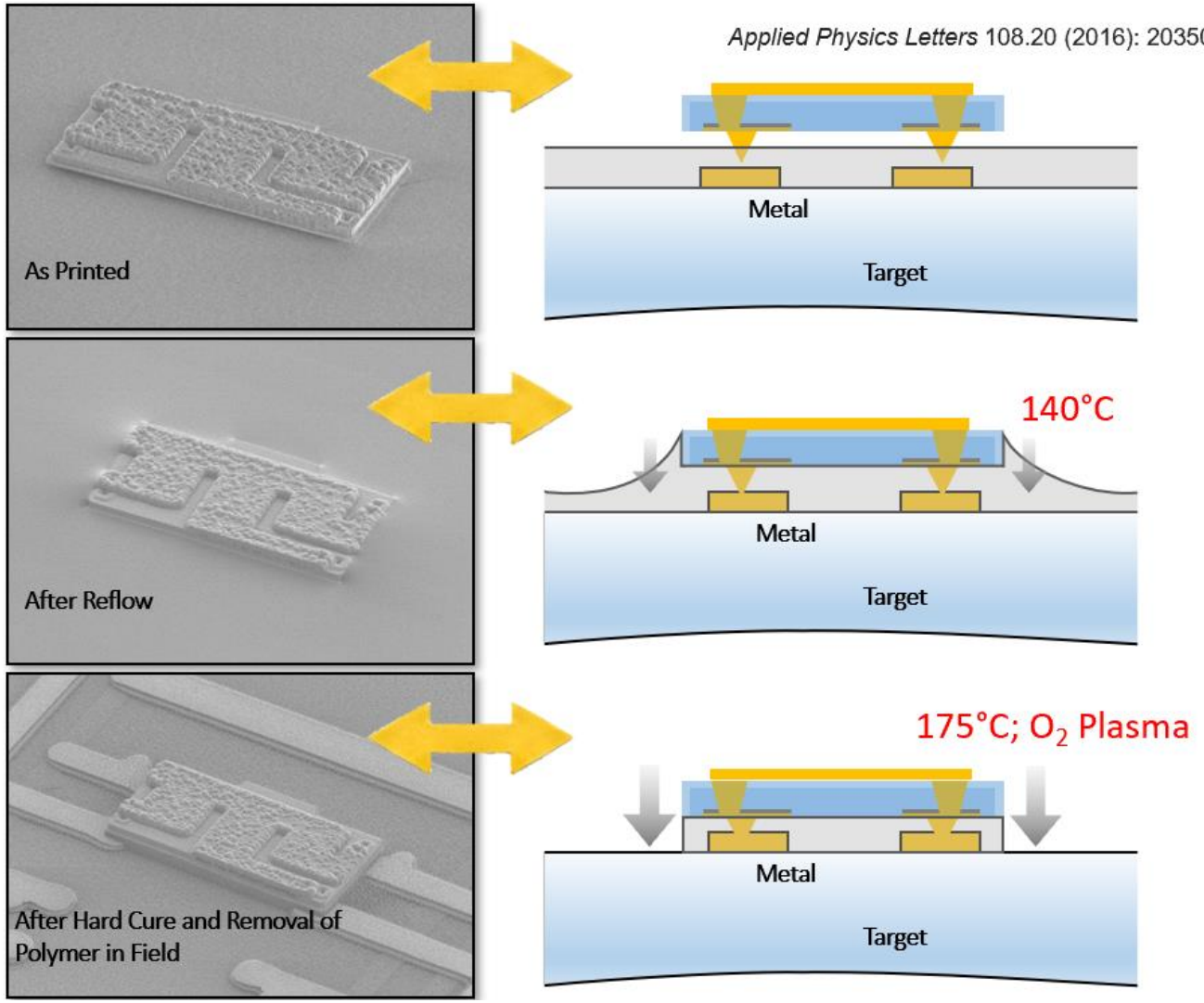




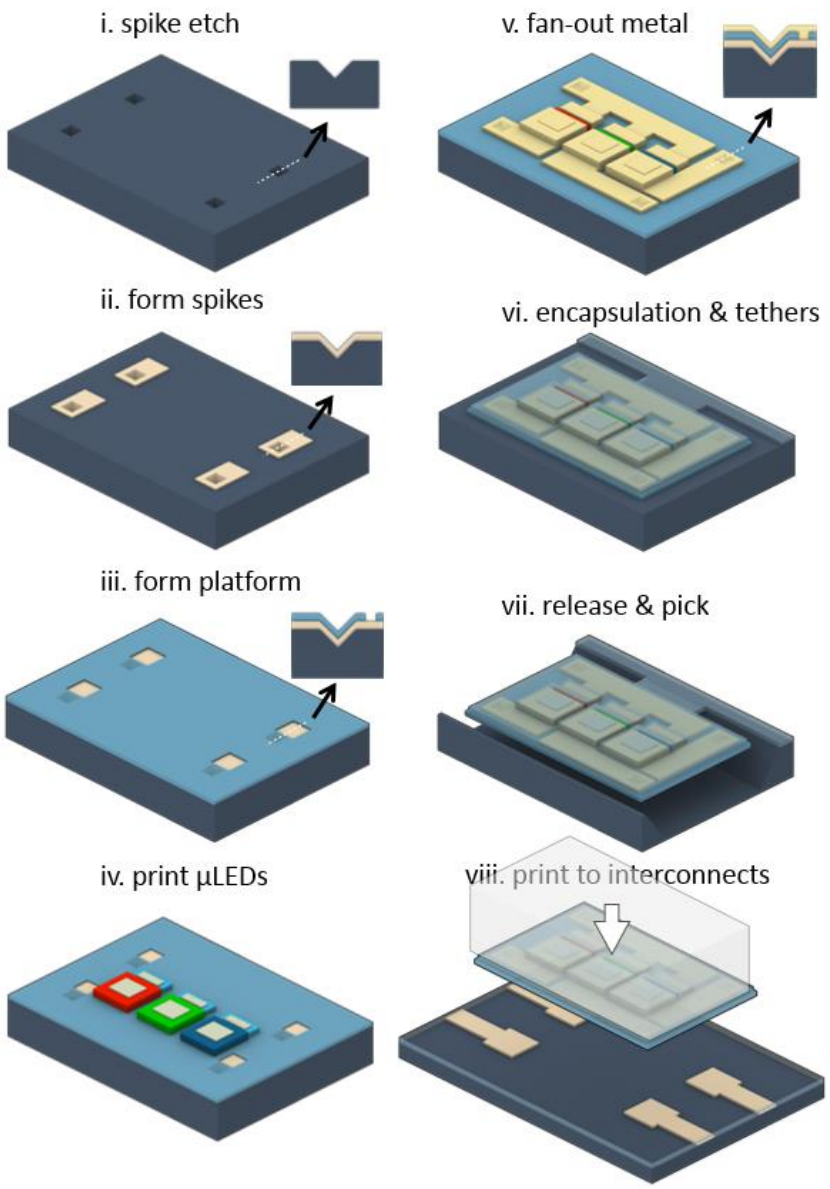
Interconnect @ Print

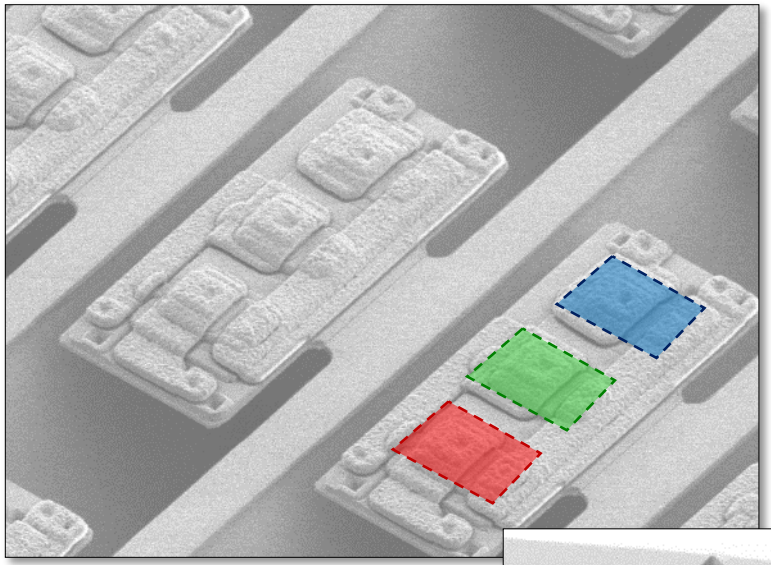
A silicon template to make conductive "spikes"

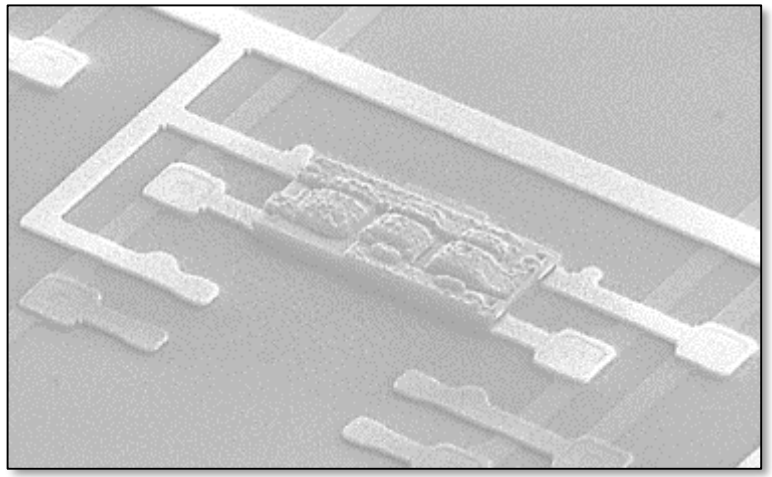


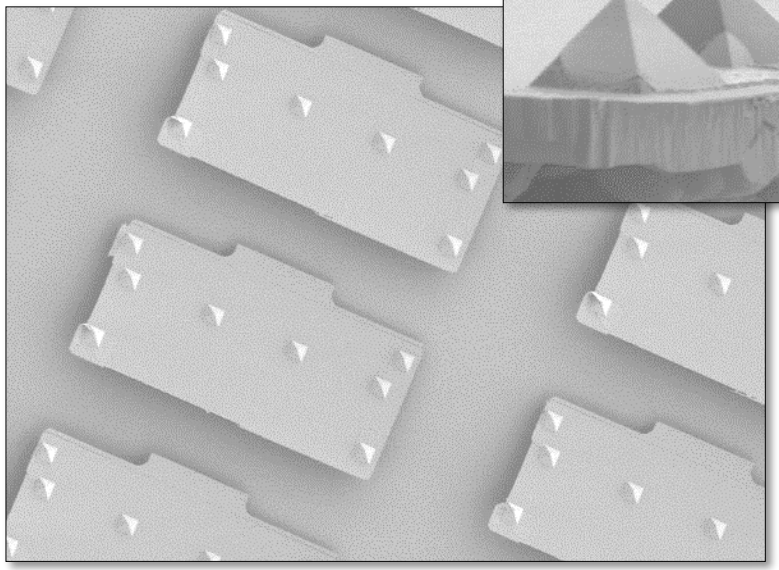


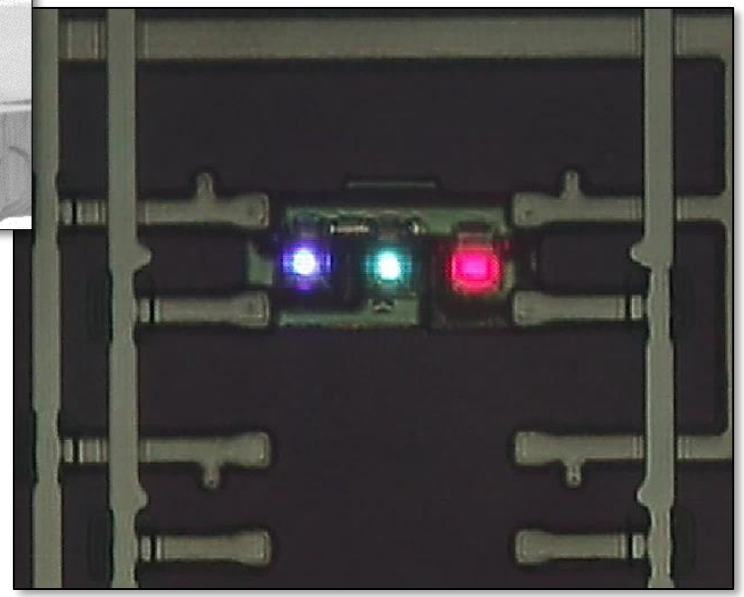
Transfer-ready pixel engines



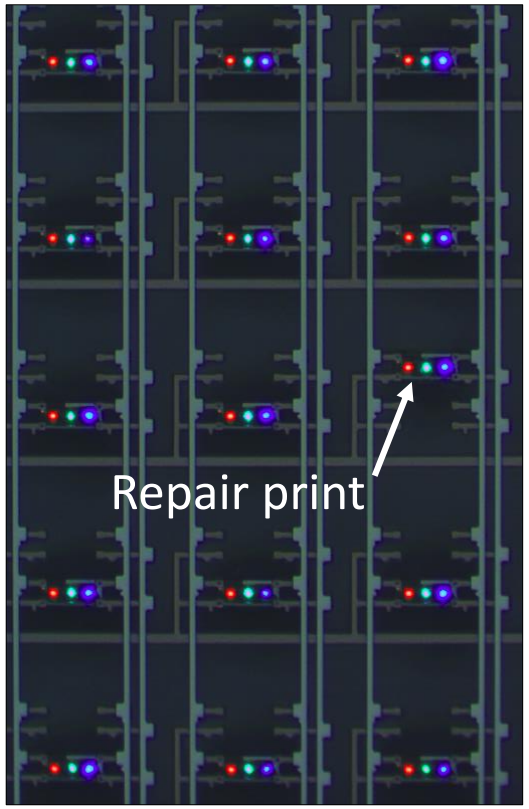


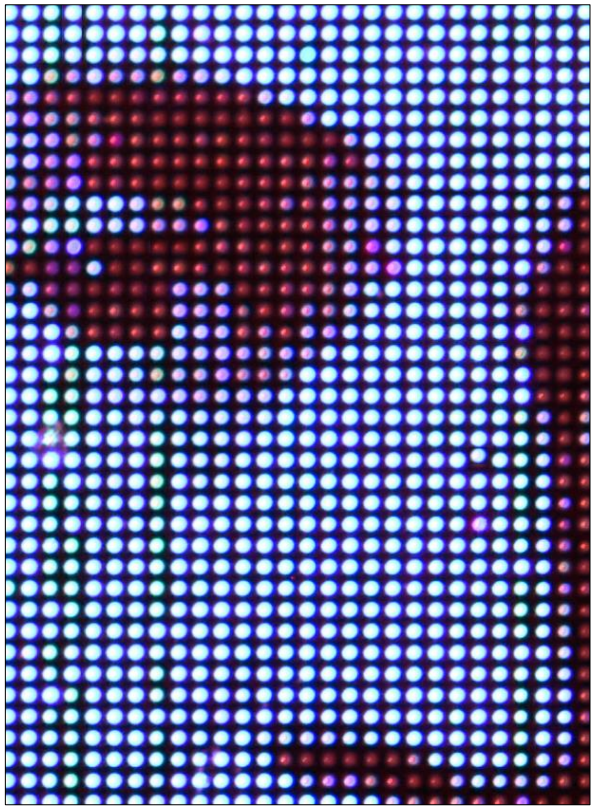




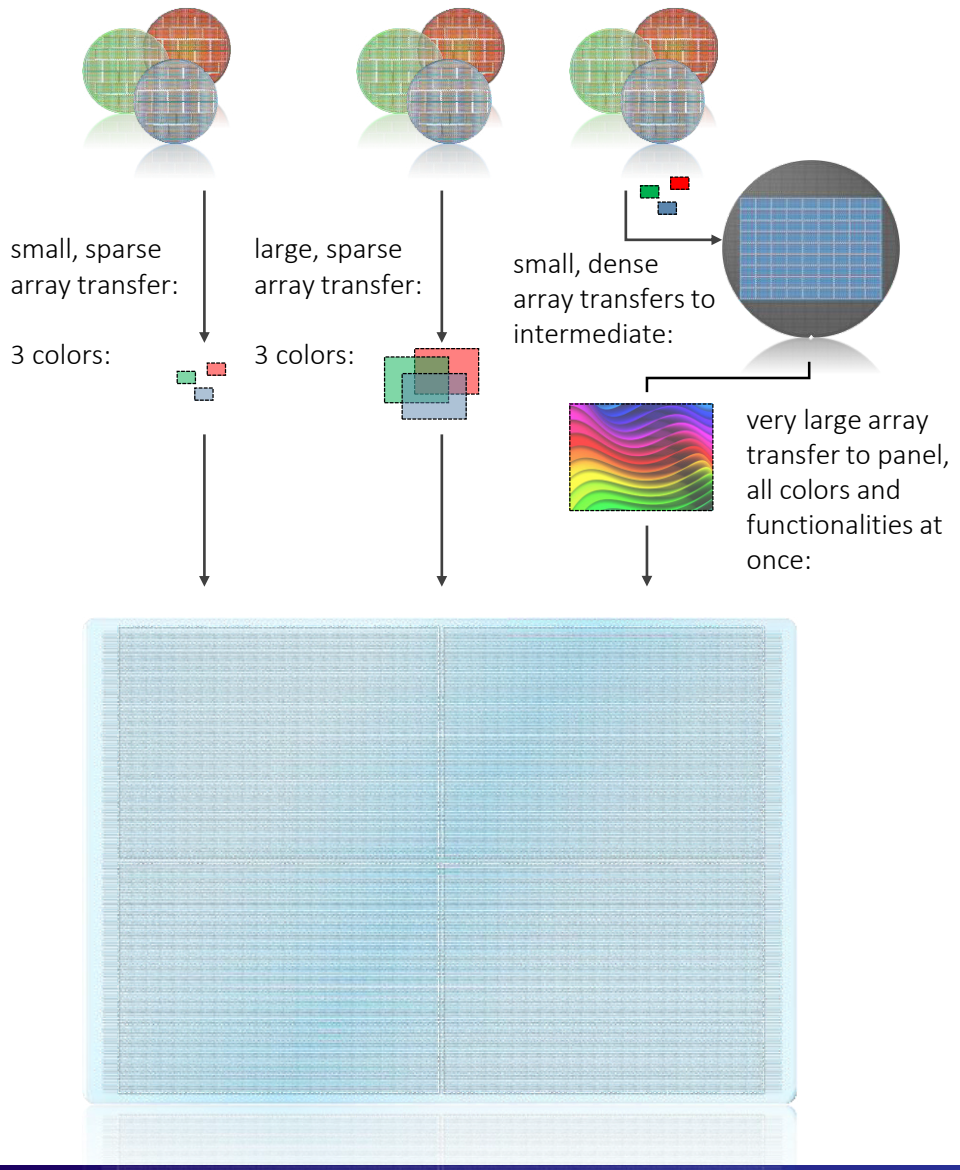


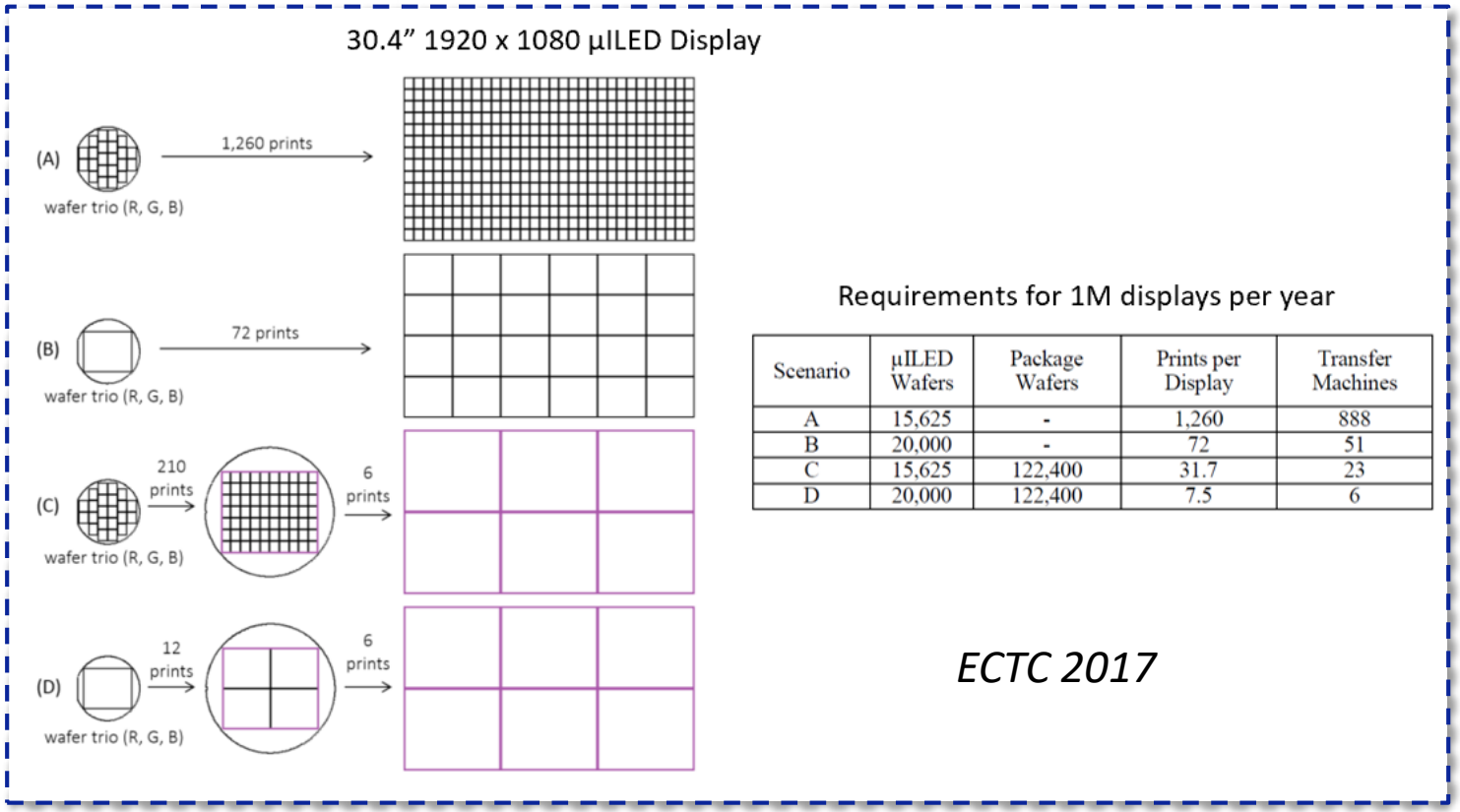
Additive repair using i@p engines





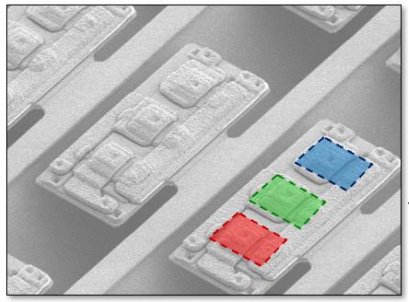
Intermediate Substrates for Throughput & More





Scenario	µILED Wafers	Package Wafers	Prints per Display	Transfer Machines
A	15,625	-	1,260	888
B	20,000	-	72	51
C	15,625	122,400	31.7	23
D	20,000	122,400	7.5	6

Assembly-centric display making



transfer-ready components

receive-ready panels

capital efficient
transfer-factories

displays for all applications

Thanks from the X-Celeprint team