# Solution Processed OLEDs for Display and Lighting Applications

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# Agenda

- DuPont materials and process for OLED Displays
- Introduction to OLED lighting work at DuPont

# Future of OLED requires new manufacturing technology

## Evaporation with fine metal masks has very high cost

- Material waste is very high
- Motherglass size is limited
- Evaporators are expensive
- Shadowmasks are costly and have to be cleaned, inspected and replaced

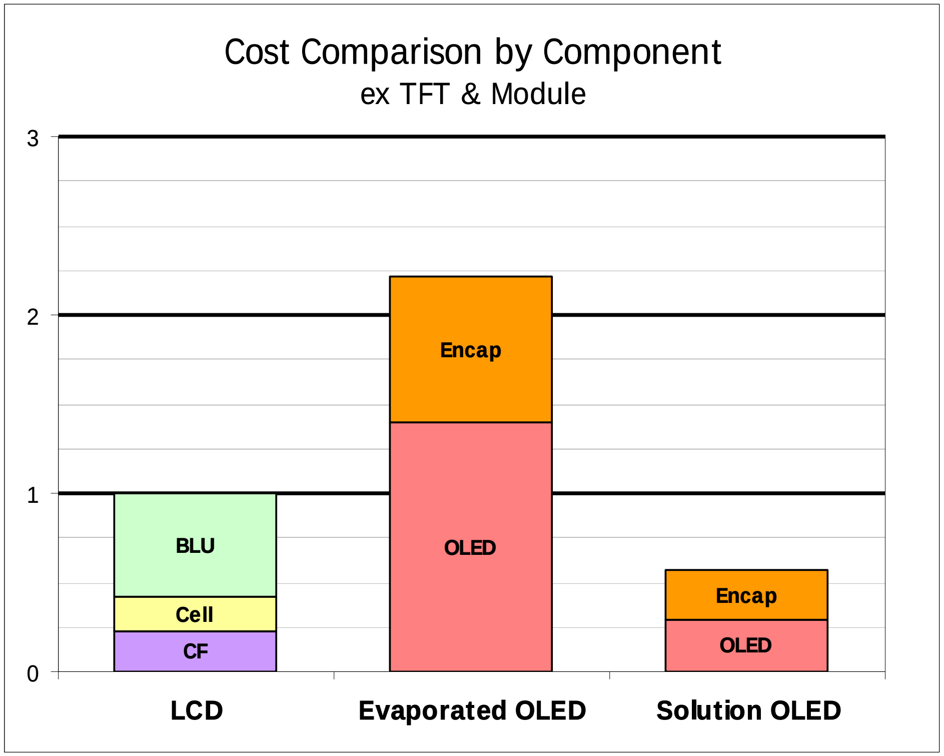
## Solution printing a good answer

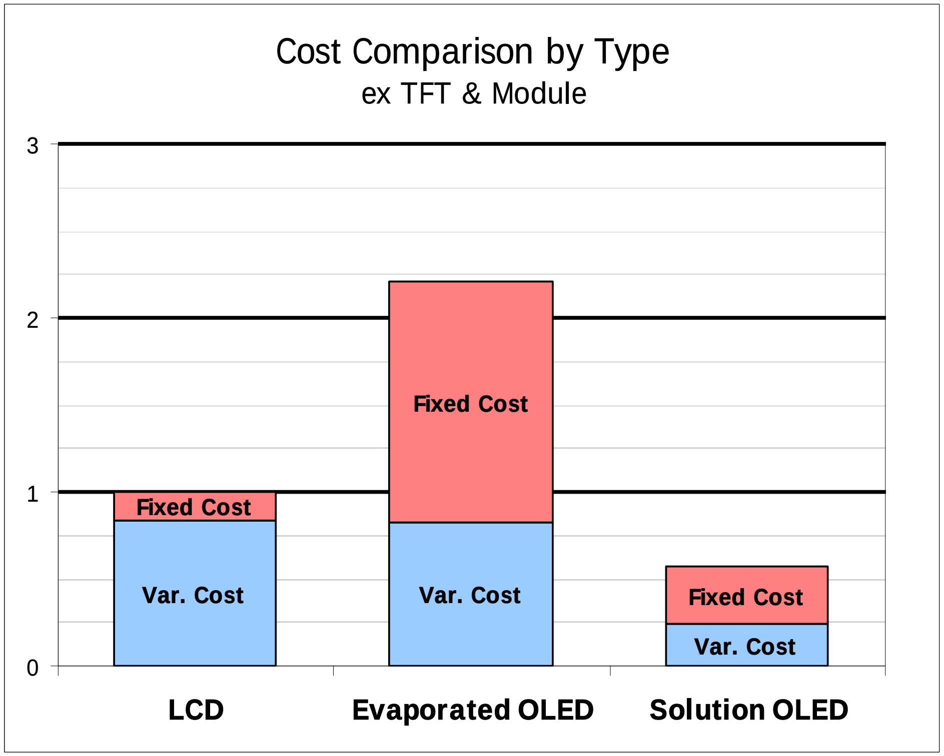
- High material utilization
- Printing can scale to any size motherglass
- Printers are much less expensive than evaporators
- No fine metal shadowmasks

Solution printing is the key to economical manufacturing at large motherglass size

# Solution Processing Addresses Today's Cost Issues

- Efficient material use reduces variable cost and takes advantage of OLED's smaller bill of materials (BOM)
- Low TACT, scalable processes increase fixed cost productivity
- Scalable and more economical equipment increases capital productivity
- Integrated development of both materials and processes was necessary to meet OLED performance requirements and manufacturing cost goals



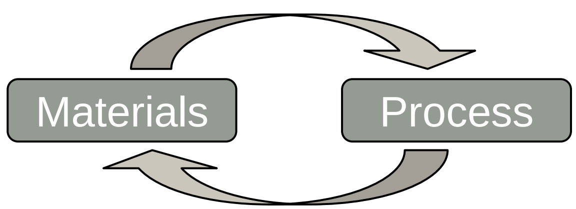



# Why isn't everyone using solution OLED already?

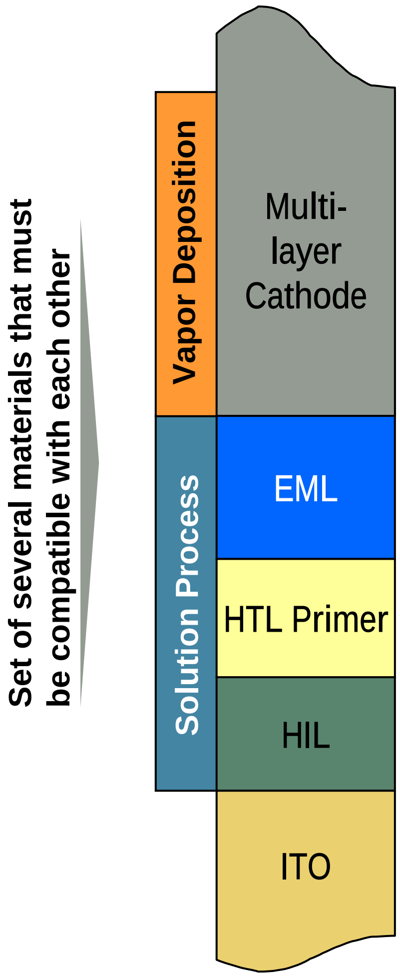
Greatest challenge is developing high-performance solution OLED materials

In addition to performance, materials development needs to help solve key process issues:

- **How to coat the "blanket" layers?**
- **How to contain the printing inks in the active subpixel area?**
- **How to keep successive layers from mixing with each other?**
- **How to clean the coated materials before encapsulation/bonding?**
- **How to print at high speed without visual defects?**
- **How to keep atmospheric conditions during printing/coating from degrading the organic materials?**



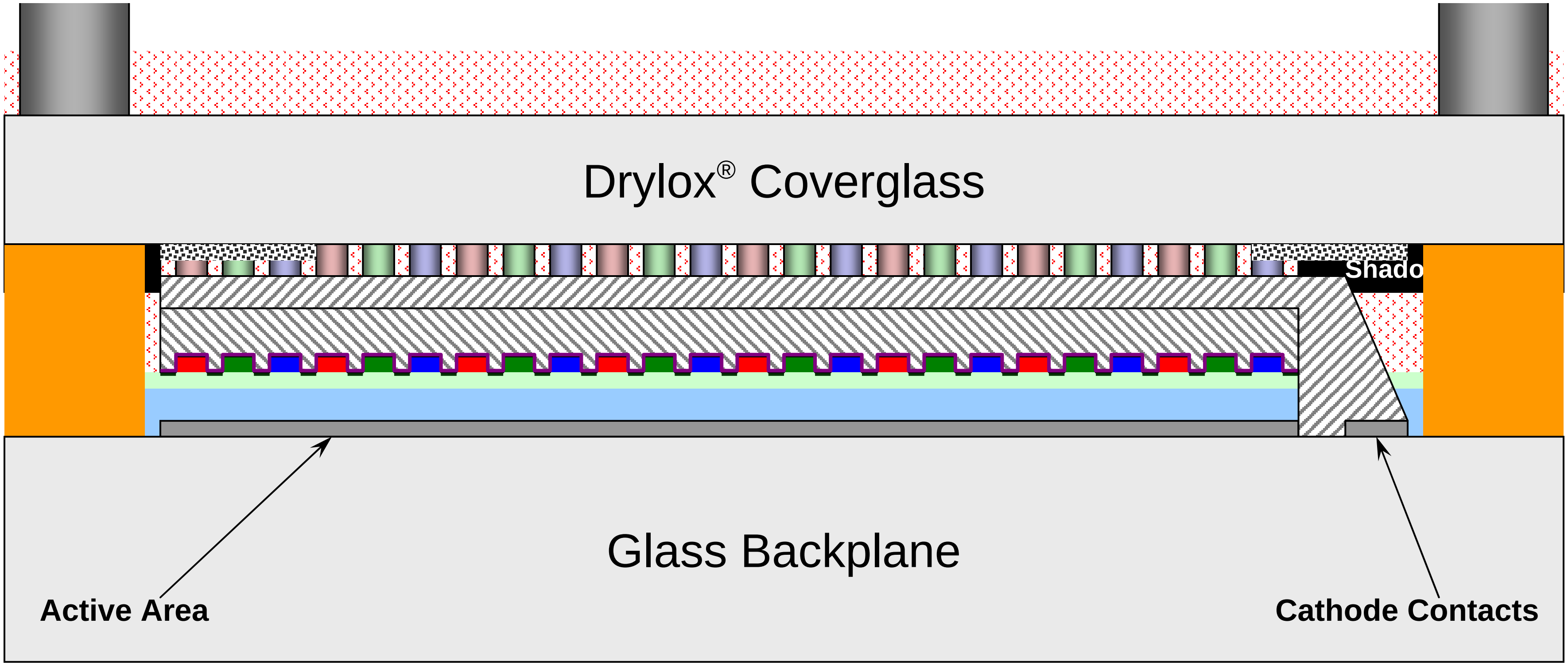
# DDI Solution OLED Process – Fundamental Principles




## ***Reduce the cost of manufacturing:***

- **Solution process as many layers in the OLED stack as possible**
  - Eliminates capital intensive processing (e.g. thermal evaporation)
  - Provides for a more efficient use of materials
  - Requires close tailoring of materials and manufacturing process
- **Pattern minimum number of layers – use common layer architecture and manage performance tradeoff**
- **When patterning is required; employ a robust, reliable tool for the patterned layer – Nozzle Printer**
- **Employ standard FPD industry equipment, e.g. slot coating**
- **When specialized equipment is required, we partner with recognized FPD equipment maker (DNS for nozzle printer)**

# DuPont Solution OLED Process Overview




**Slot coat HIL and Primer Layers**

**Modify Primer Surface to Form Wetting & Non-Wetting Lanes**

**Multinozzle Print EML Layers**

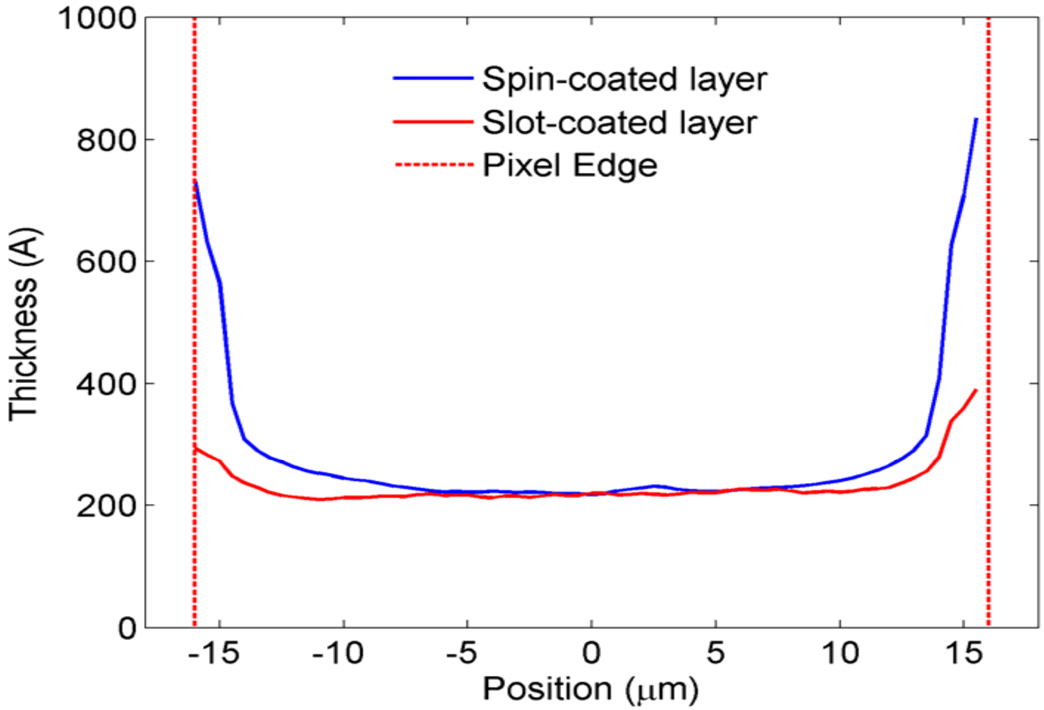
**Evaporate ETL, EIL & Metal Cathode over Active Area**

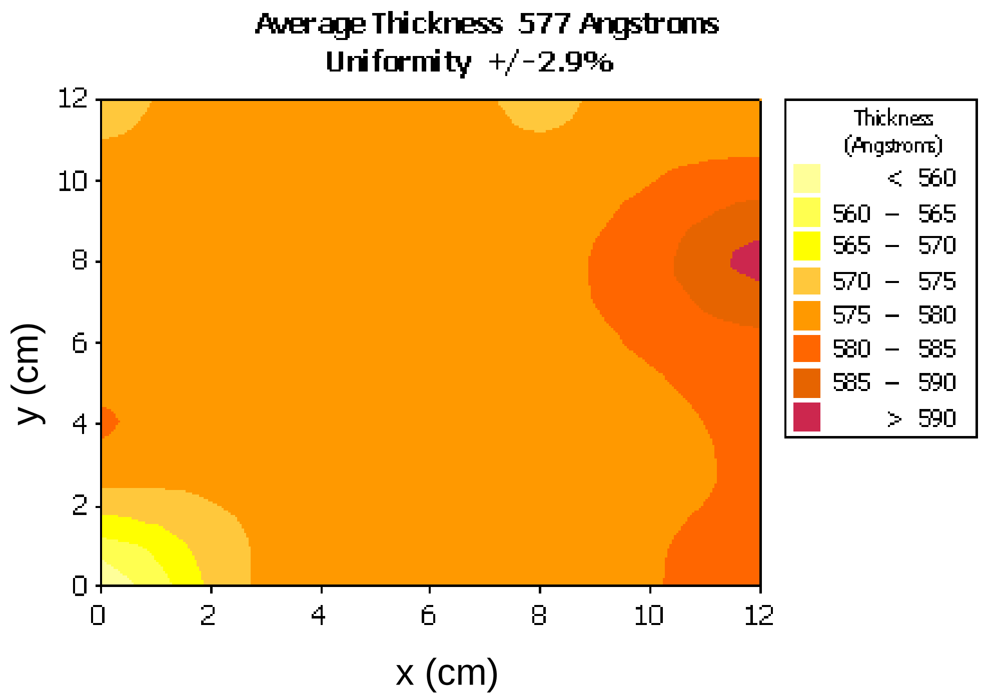
**Plasma Etch Excess Organic Layers Using Cathode as Etch Mask**

**Evaporate Cathode Connection**

**Dispense Epoxy & Encapsulate**

# Slot-die Coated Common Layers

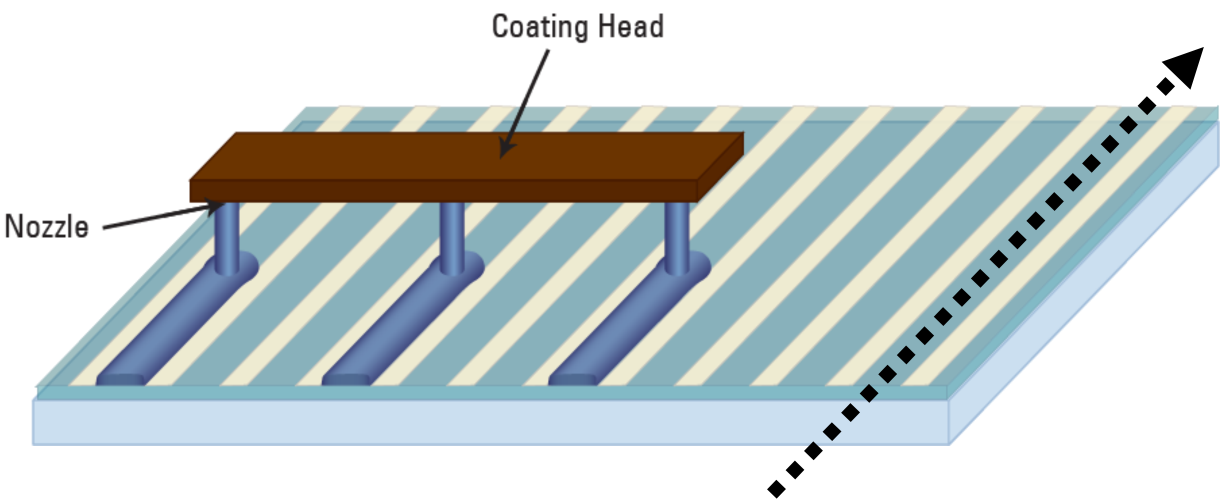


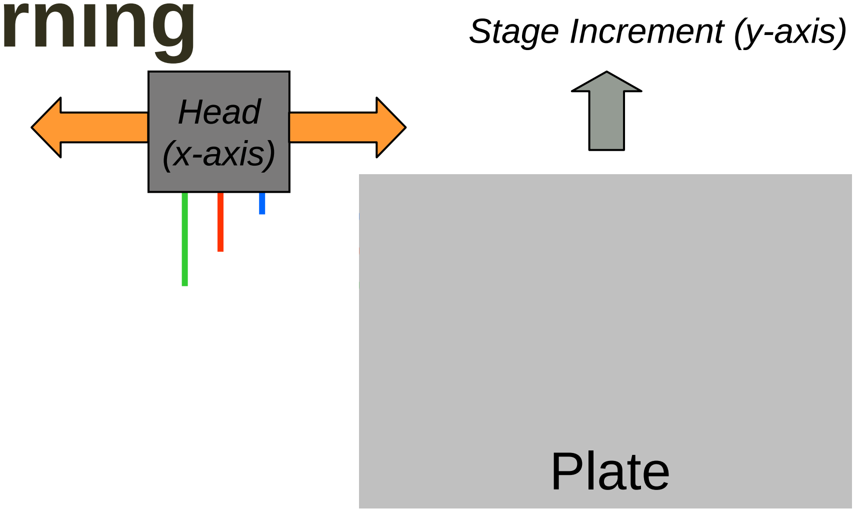
# DuPont and Dainippon Screen (DNS): Nozzle Printing for Solution OLED Display Patterning

**1st Gen 4 production scale printer installed in Santa Barbara in 4Q, 2008**
(for 730mm x 920mm glass)

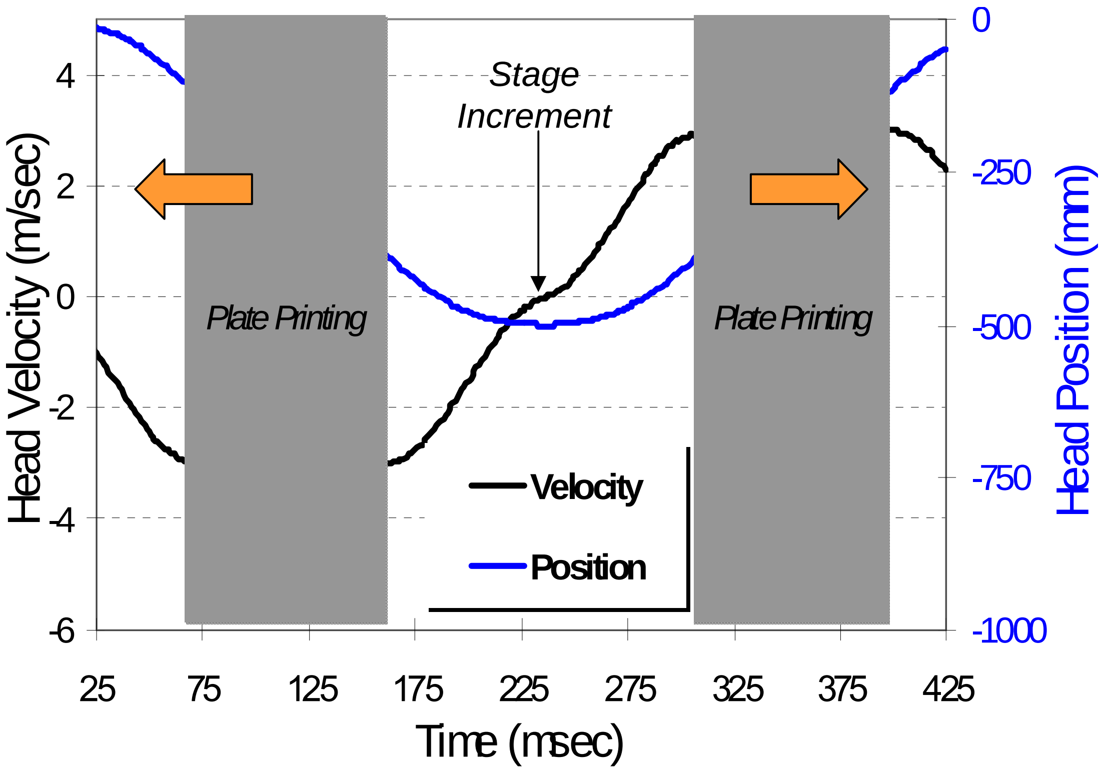
- **High throughput – 15 nozzles**
- **TACT is <3 min per Gen 4 substrate**
- **Excellent printing uniformity**
- **High material utilization**




# Nozzle Printer Patterning

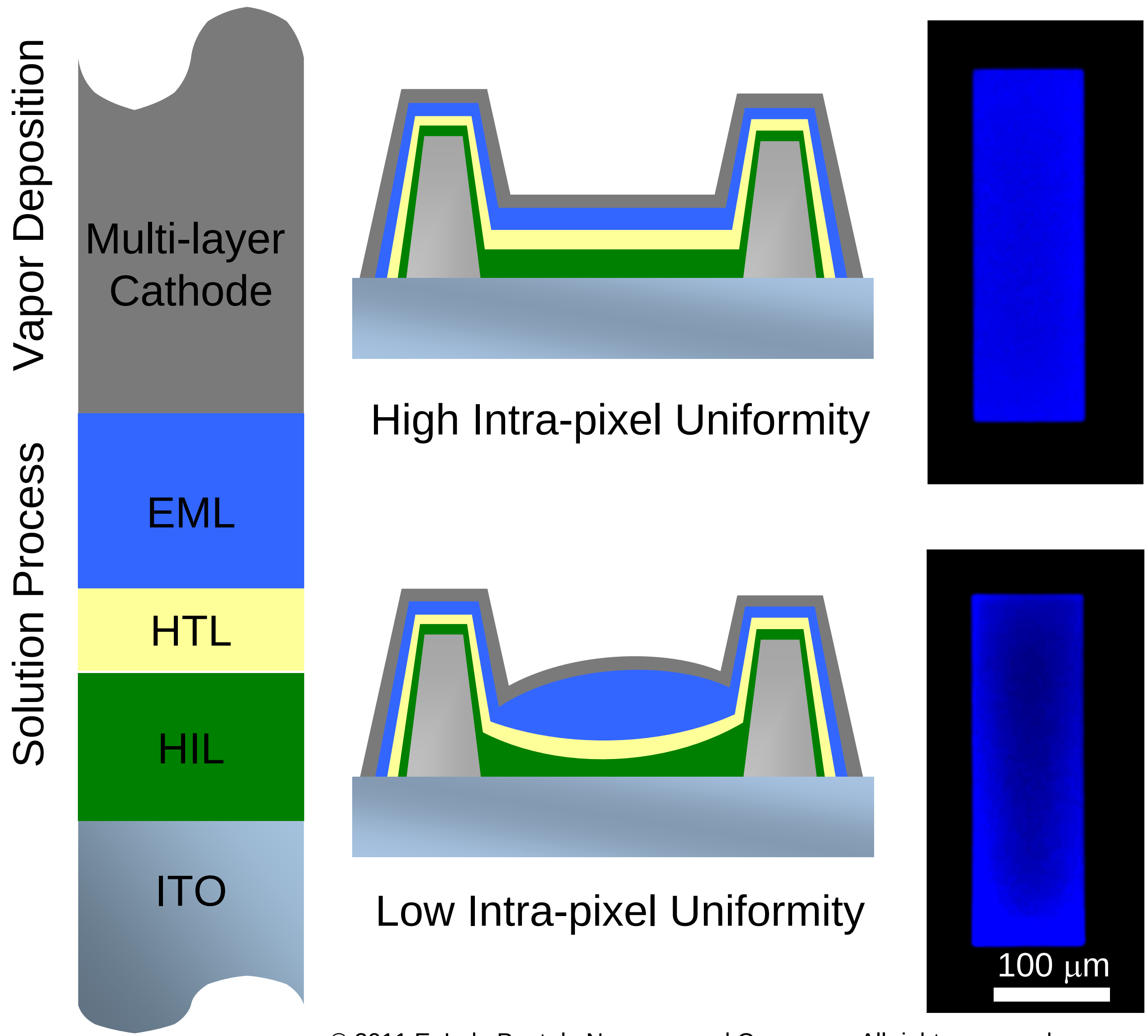



- Synchronized x- and y-axis movement
- Head velocity 2 - 5 m/s
- Acceleration up to 10G



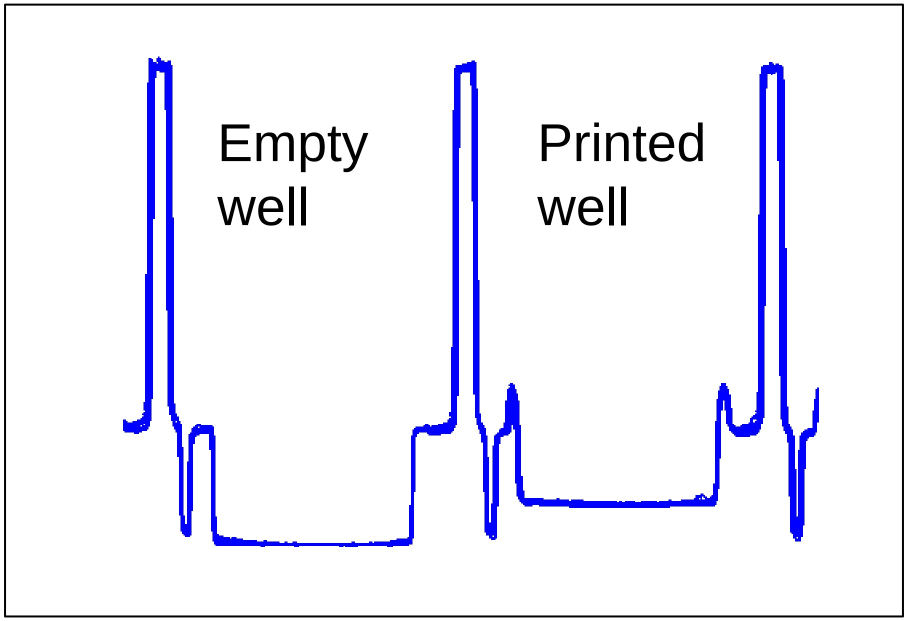
# Intra-pixel uniformity

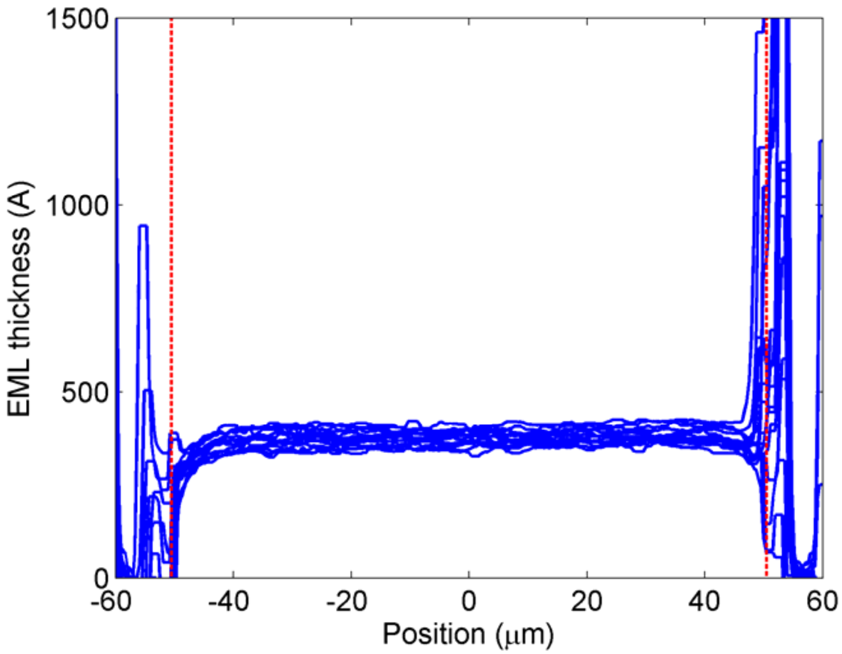
## Low in-pixel uniformity lowers device performance, introduces mura



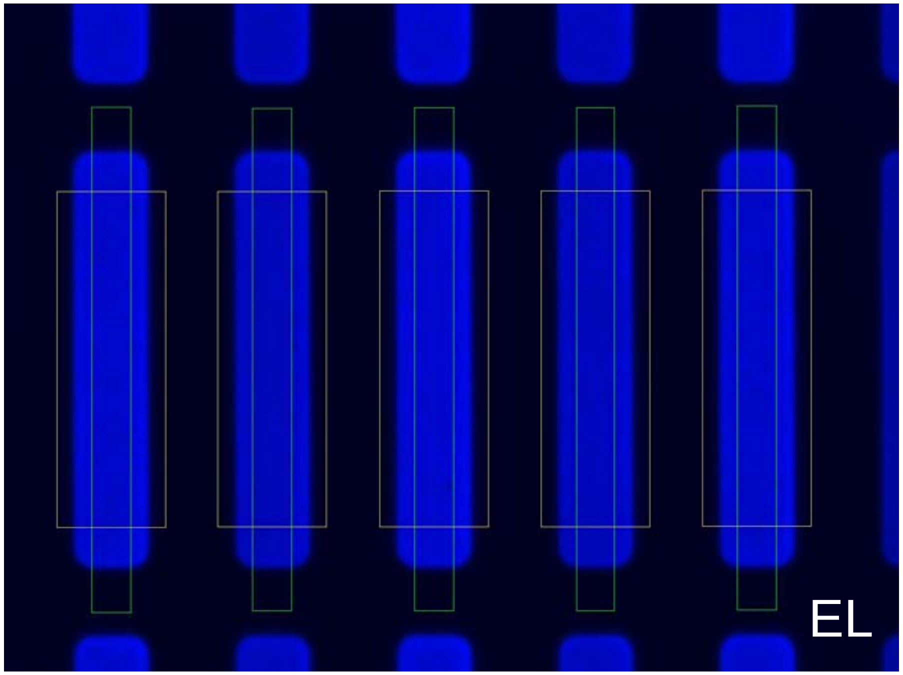
# Intra-Pixel Thickness Uniformity Measurement

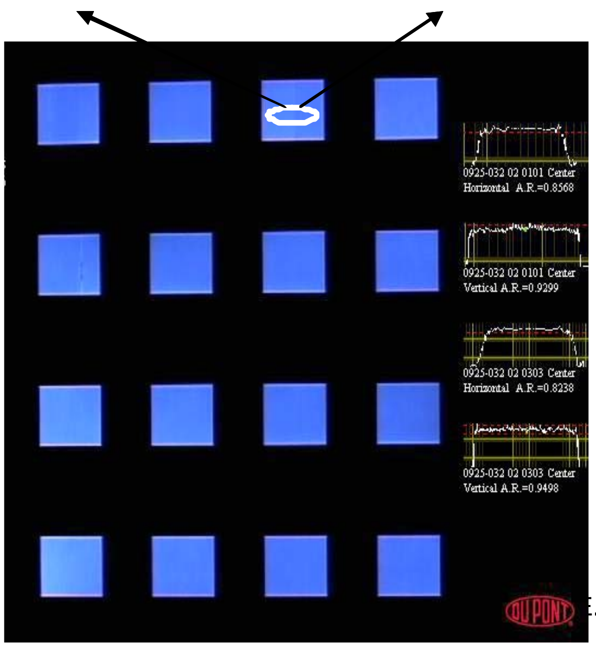
- Use stylus profilometer to scan 16 locations on a 150x150 mm printed substrate.
- Custom software analysis extracts printed layer thickness throughout the pixel.
- > 95% thickness aperture is achievable.
- ~ 2 nm thickness variation across the plate: Long range uniformity >  90%

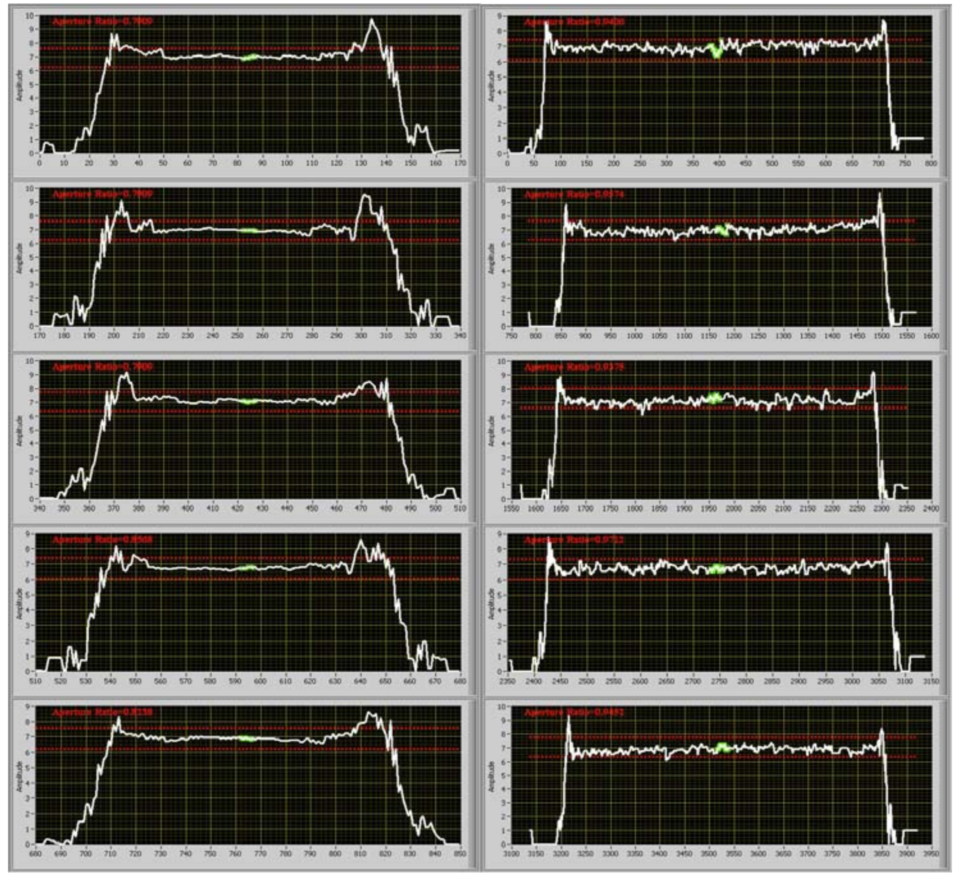


# Intra-Pixel Luminance Uniformity – Standard Printed Parts



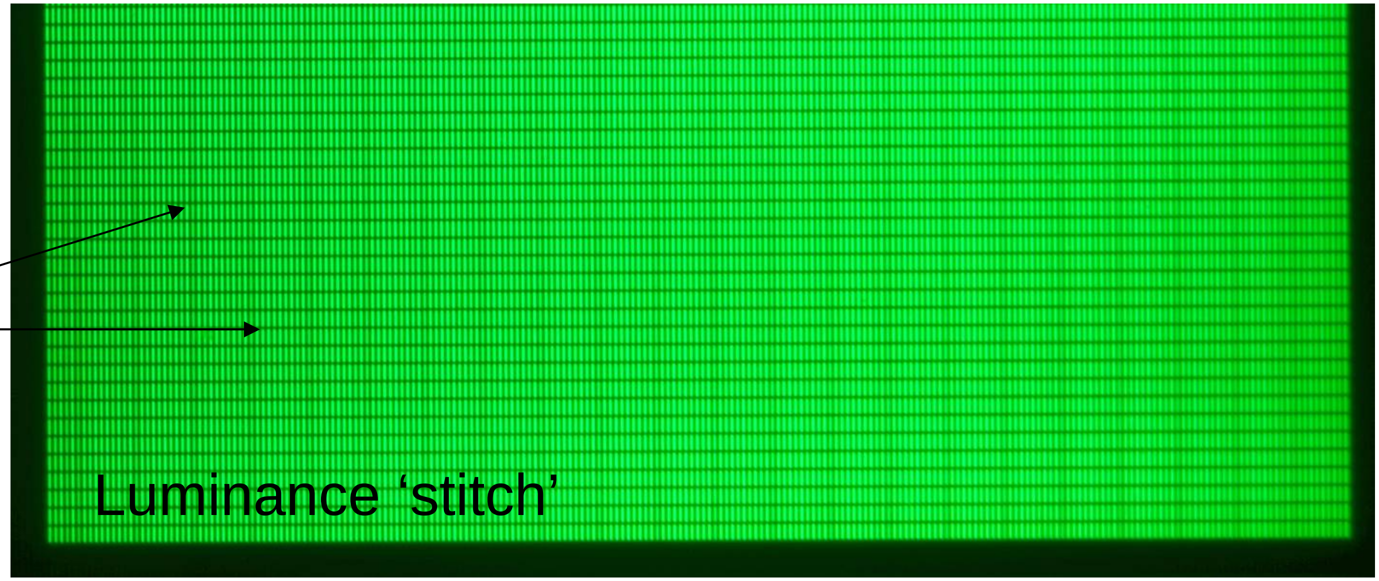
**Horizontal Results** **Vertical Results**

**Achieved by high intra-pixel layer uniformity for all solution coated layers**

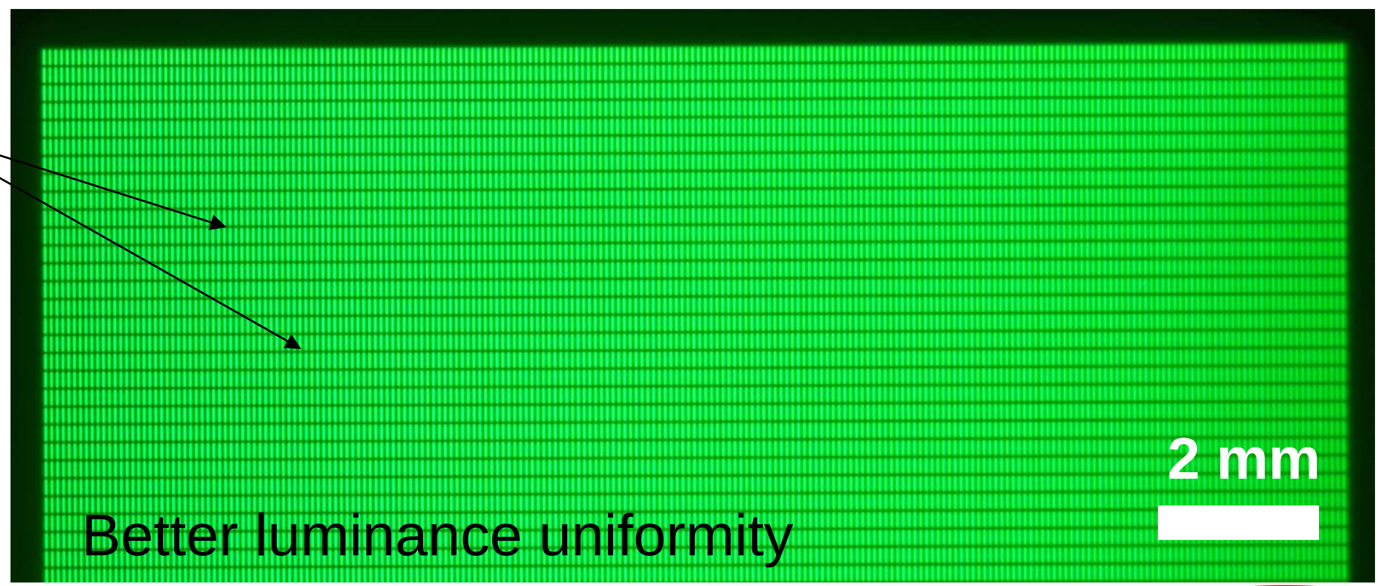
# Inter-Pixel Short Range Uniformity:
# Luminance Stitch from Multi-Nozzle Printing

Periodic luminance variation

~7%



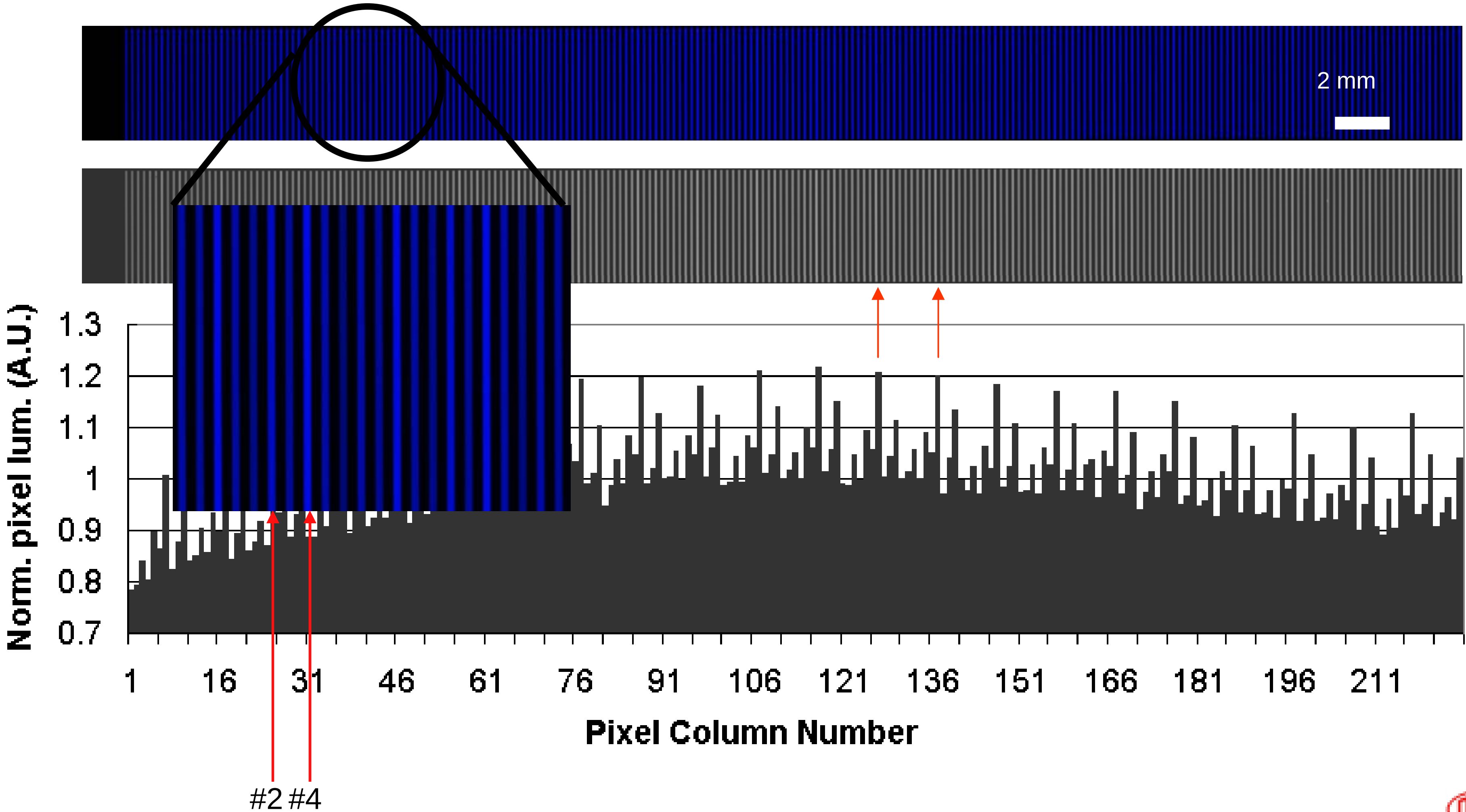

<3% periodic luminance variation




*PM monochrome green, 5 nozzle printing*

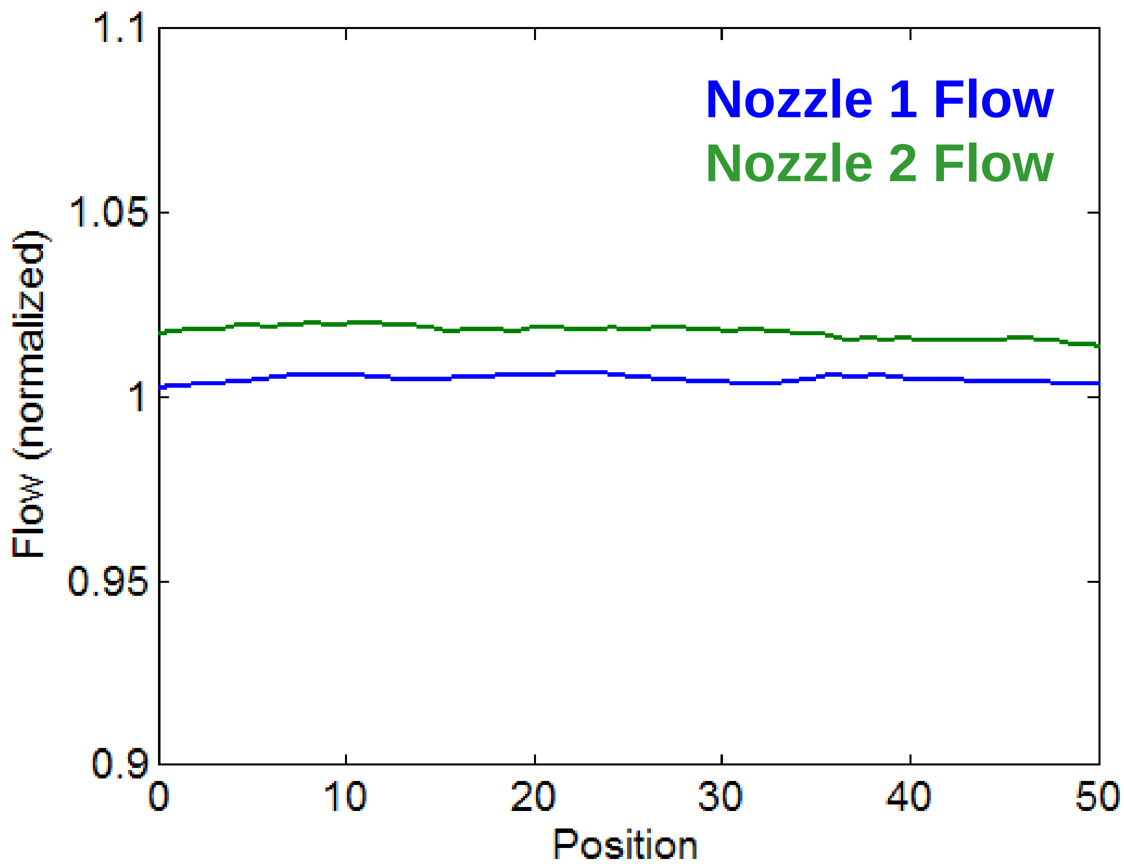
# Inter-Pixel Short Range Uniformity: Measuring Visible Multinozzle Stitch

This example (5 nozzles) shows Nozzle #2 and #4 produce pixels which are noticeably different than the other three nozzles

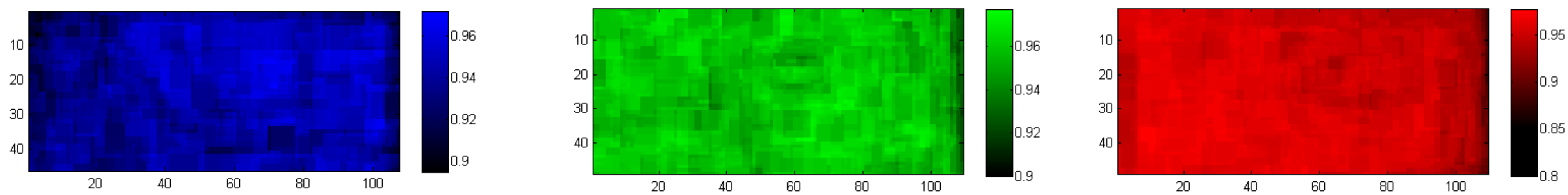


# Sensitivity of Stitch Optical Measurement

Small intentional offset in flow used to test the sensitivity of the measurement



# Assessing Inter-Pixel Short Range Uniformity Using a Display Industry Metric



$$Ush = \frac{\sum_{i=0}^{n-1}\sum_{j=0}^{m-1} Ur_{ij}}{n \times m}$$

$$Ur_{ij} = 1 - \frac{L_{64\max} - L_{64\min}}{L_{64\max}}, L_{64\max} = \max_{i=0...7, j=0...7} L_{ij}, L_{64\min} = \min_{i=0...7, j=0...7} L_{ij}$$

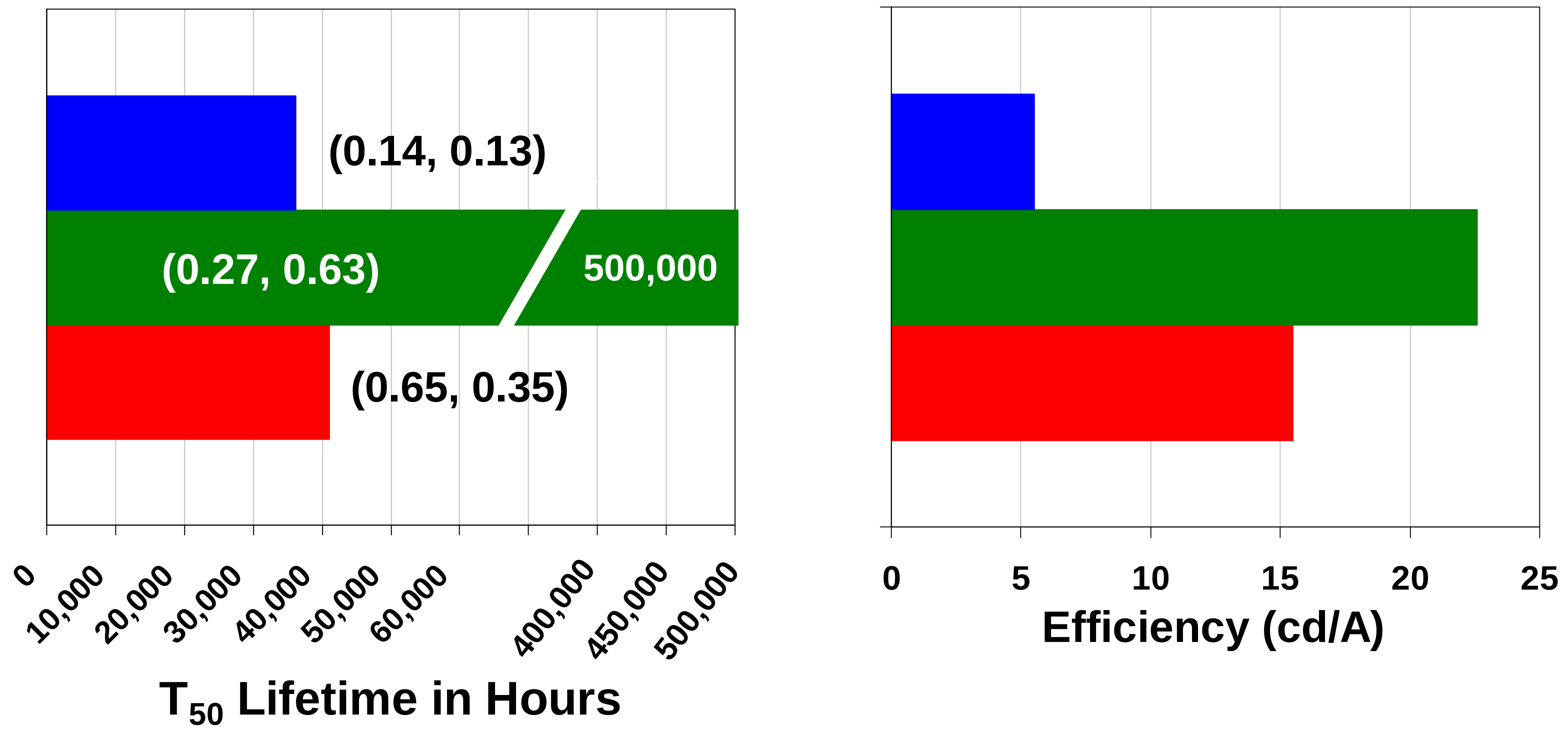
| Item | $U_{SH}$ |
|---|---|
| AMOLED Blue sub-pixels | 0.94 |
| AMOLED Green sub-pixels | 0.94 |
| AMOLED Red sub-pixels | 0.95 |
| Commercial AMLCD* | 0.93 |

* A. Arkhipov, B-w. Lee, K. Park, C. Kim, and J. Lee, “New Metric for Short-Range Uniformity of AMOLEDs”, IMID Digest P-81, pp. 488-491 (2008)

# The transition to commercial printed devices – multinozzle printing for rapid TAC time

Uniform monochrome display
printed with
five nozzles on G4 printer
4.3” dia. 128 ppi

# Printed Lifetime $T_{50}$ Adjusted Display Life Time (100% on)

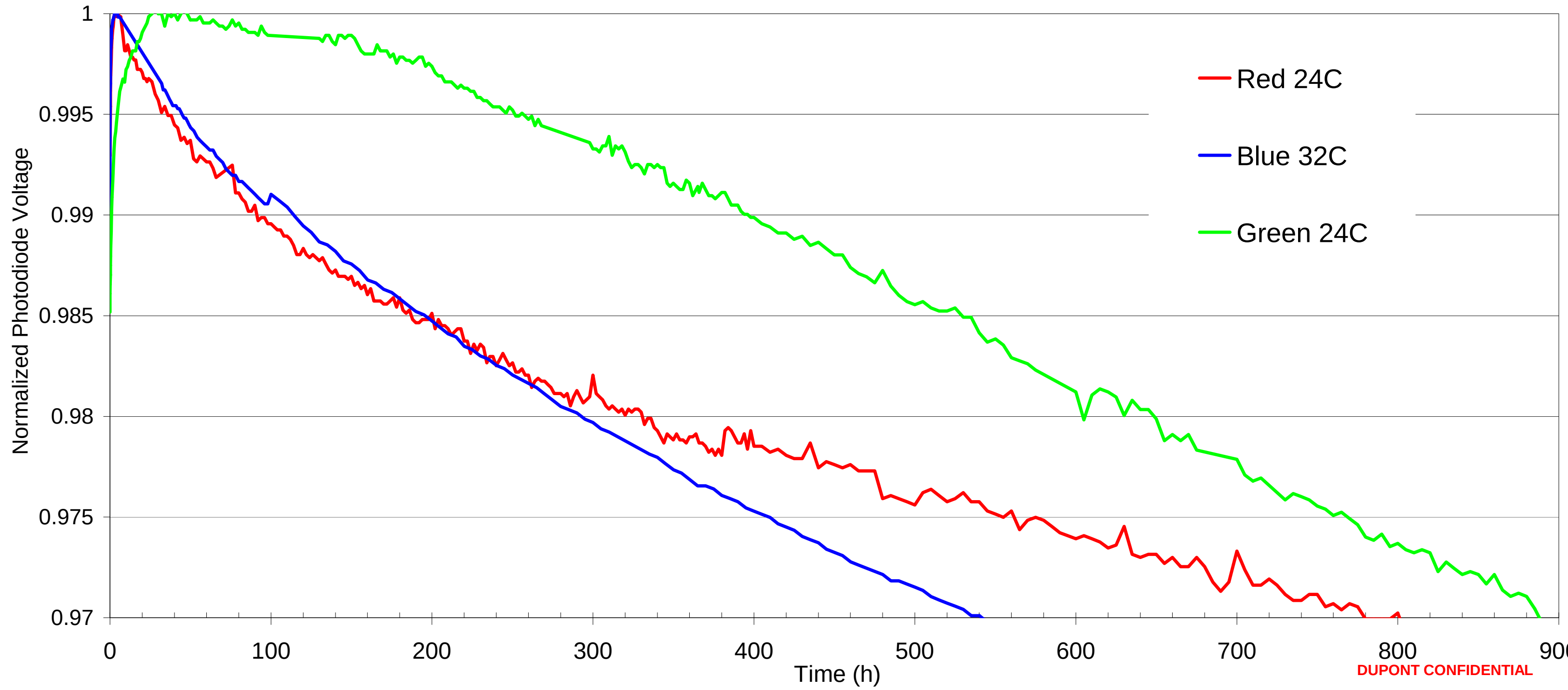



Printed bottom emission test coupons with no outcoupling enhancement. Common architecture converted to 200nits front-of-screen (white point CIE 0.31,0.32) with 40% aperture ratio, 46% transmission circular polarizer at 100% duty cycle.
Lifetime data reported at 20°C

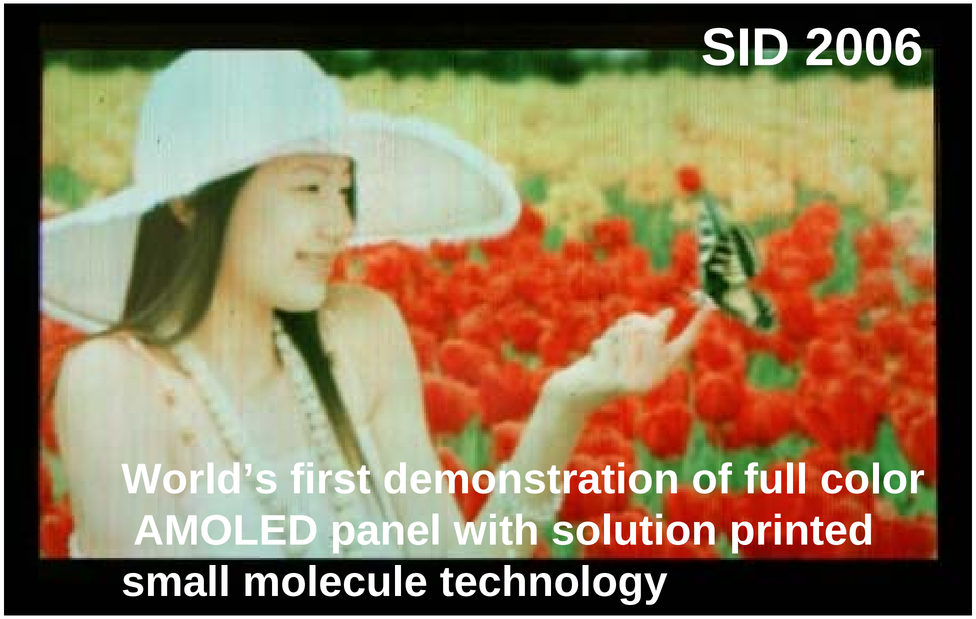
# New Material Solutions to Address Image Sticking: Spin Coated Test Coupons, Common Architecture, No Burn-In

| Color | Luminance (nits)[1] | Efficiency (cd/A) | Voltage | CIE (x,y) | T97 (hours) | Lifetest Temperature (°C) |
|---|---|---|---|---|---|---|
| Red | 914 | 20.6 | 5.8 | (0.65, 0.35) | 800 | 24 |
| Green | 1845 | 89 | 3.9 | (0.34, 0.63) | 900 | 24 |
| Blue | 934 | 6 | 4.8 | (0.14, 0.14) | 500 | 32 |

[1]Simulates 200 nit FOS white with CIE = (0.28, 0.29), 40% AR, and 44% polarizer transmittance



# Progress of DDI Solution Processing






# SID Demos



## 2010

**4.4" AMOLED**
**Segment of 40 " HDTV**
Printed solution-processed display

## 2011

**5.8” AMOLED**
**83 ppi**
**1.1 mm thick**

# Summary- OLED Display Materials/Process Development

- Solution processing is a key to cost competitive large area OLED displays

- DuPont proprietary materials and associated process technology can now deliver lifetime and color performance in line with anticipated first product OLED TV demands in a solution-processed, printed device.

- The challenges of rapid and large area patterning have been largely resolved using these materials and an understanding of their device physics, coupled with process engineering tied to the materials' properties.

# Agenda

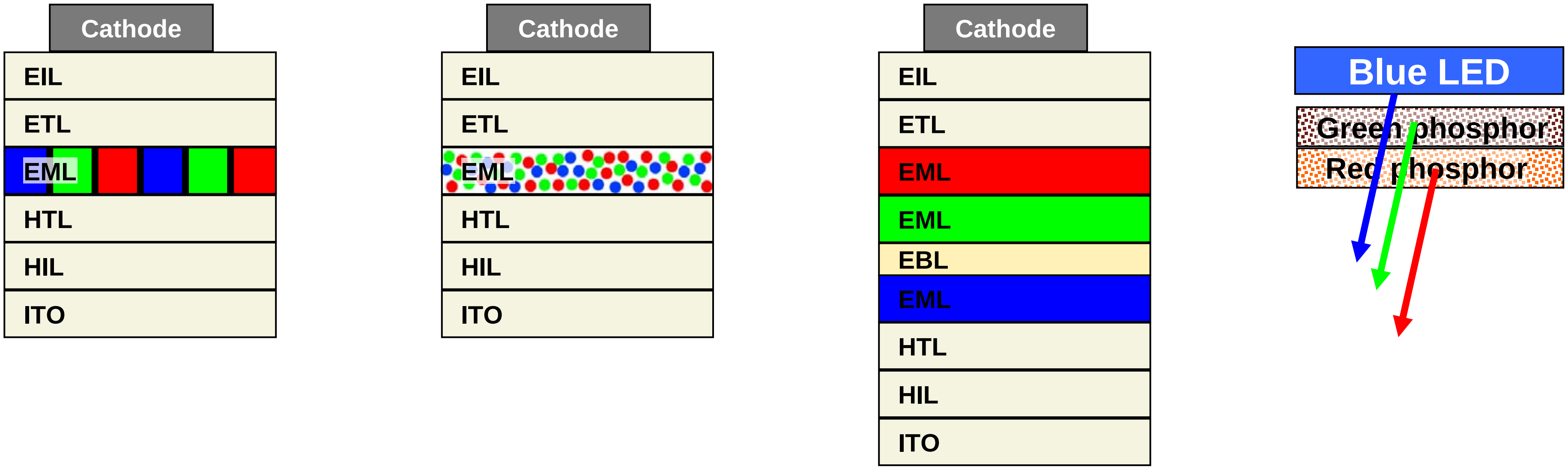
- DuPont materials and process for OLED displays

- Introduction to OLED lighting work at DuPont

# OLED Lighting Challenges

- **OLED form is exciting, but not compelling by itself**
  - Counting on OLED's unique planar form factor to drive adoption is NOT a viable strategy considering the investment to be made
  - OLEDs must deliver the lowest total cost of ownership along with unique functionality
- **Lighting cost targets are brutal**
  - Manufacturing cost will dominate the cost equation for OLED lighting
- **Window of opportunity may be short**
  - LED lighting is already (somewhat) commercial, continues to improve and is becoming less expensive

# Many Ways to Generate White Light with OLEDs




Evaporation ⟷ **process** ⟷ Solution Deposition

Multiple Layers ⟷ **architecture** ⟷ Single Layer

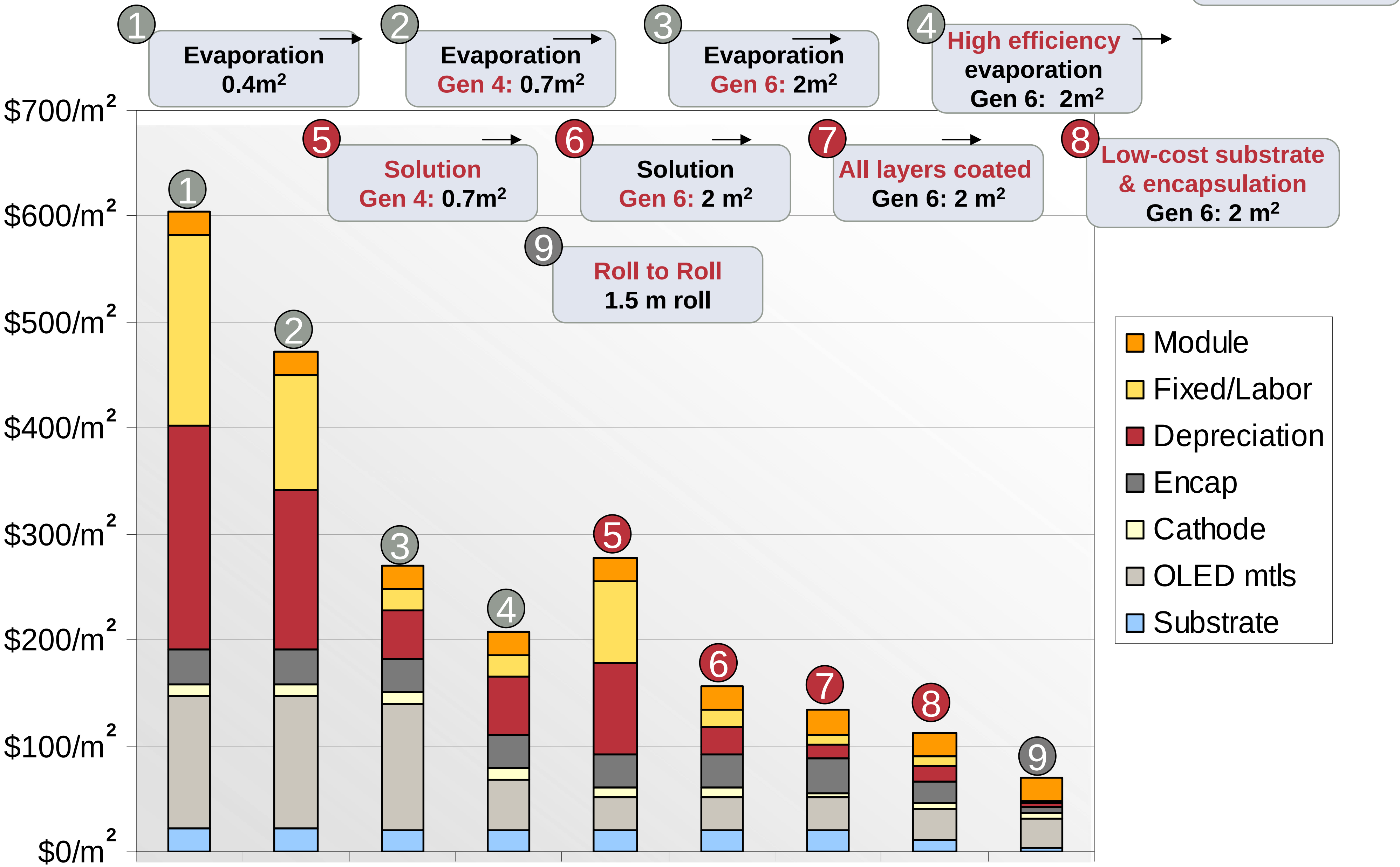
In lighting, cost dominates.
We need to choose a manufacturable structure and develop the technology to enable it

# Five Ways to Reduce Cost

- Minimize layers
- Scale up (size and volume)
- Reduce material cost and waste
- Low cost lighting substrates
- Reduce encapsulation cost

# Manufacturing cost roadmap

**Process**
**Substrate**

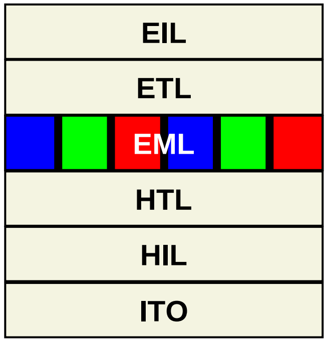



*Module cost assumes 0.4m² lamp*

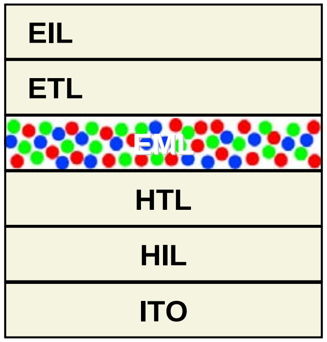
# Overview of OLED Lighting Work at DuPont

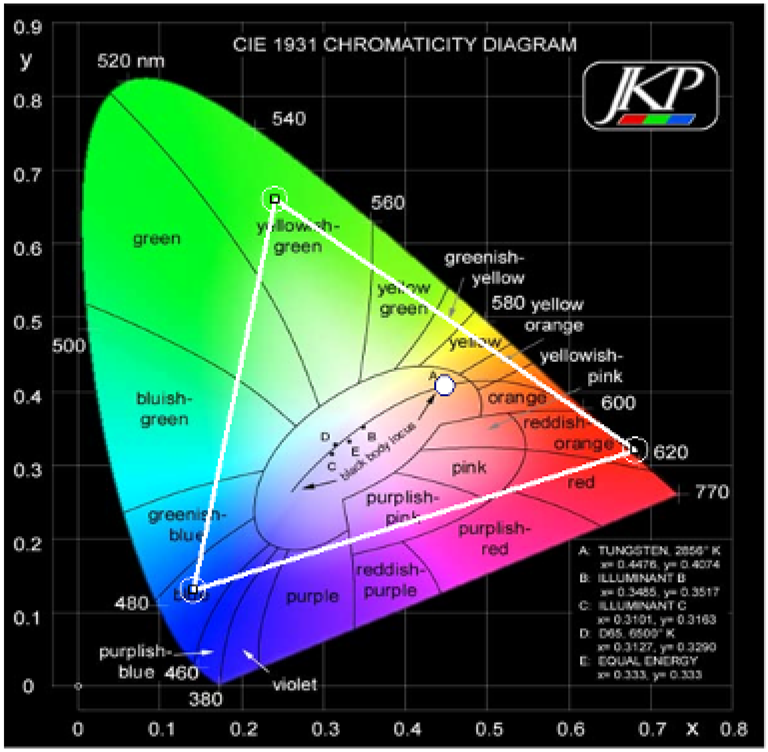
OLED Lighting represents a new area for DuPont. Two research programs have recently been activated.

1. We received a US Department of Energy (DOE) grant to evaluate printing of OLEDs for color tunable lighting (spatially separated emitters)




2. We are a subcontractor for GE on program supported by DOE to develop solution-coated, roll-to-roll manufacture of OLED Lighting (single emissive layer coated from solution)

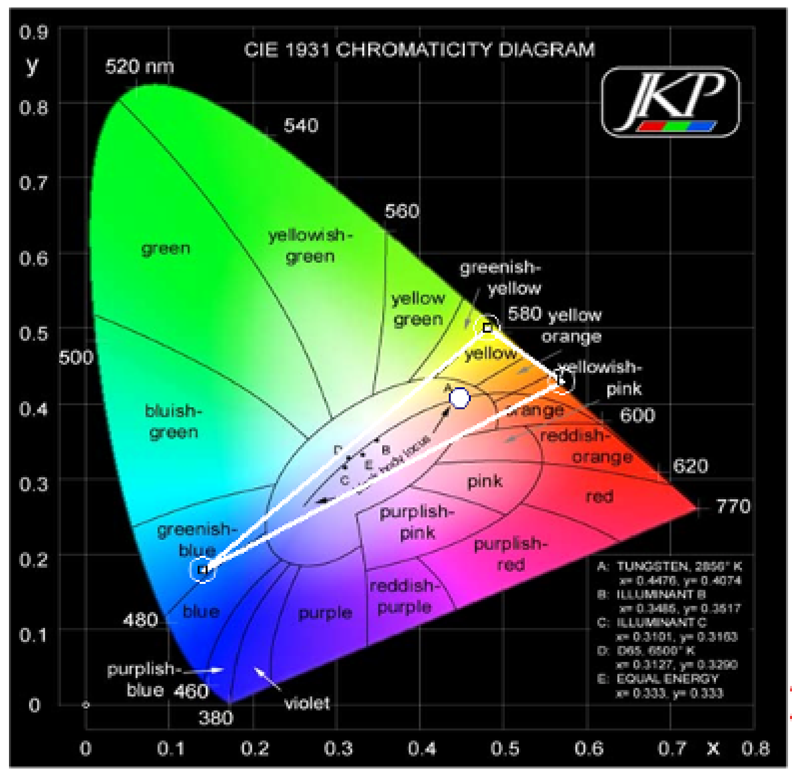





For <u>displays</u> we choose materials that give us a large ‘color gamut’ in order to best represent video images

We don’t need this wide range of colors for white lighting.

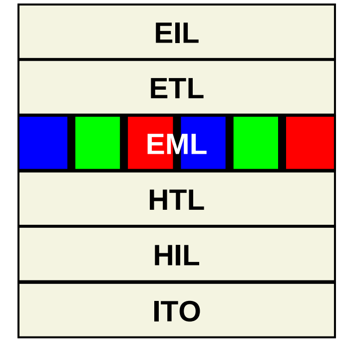
We can select our best materials based on highest efficacy instead.




While our standard materials are certainly capable of achieving the SSL color gamut, our models suggests that an alternative materials set (with lower gamut) can give 3x higher lm/W performance.

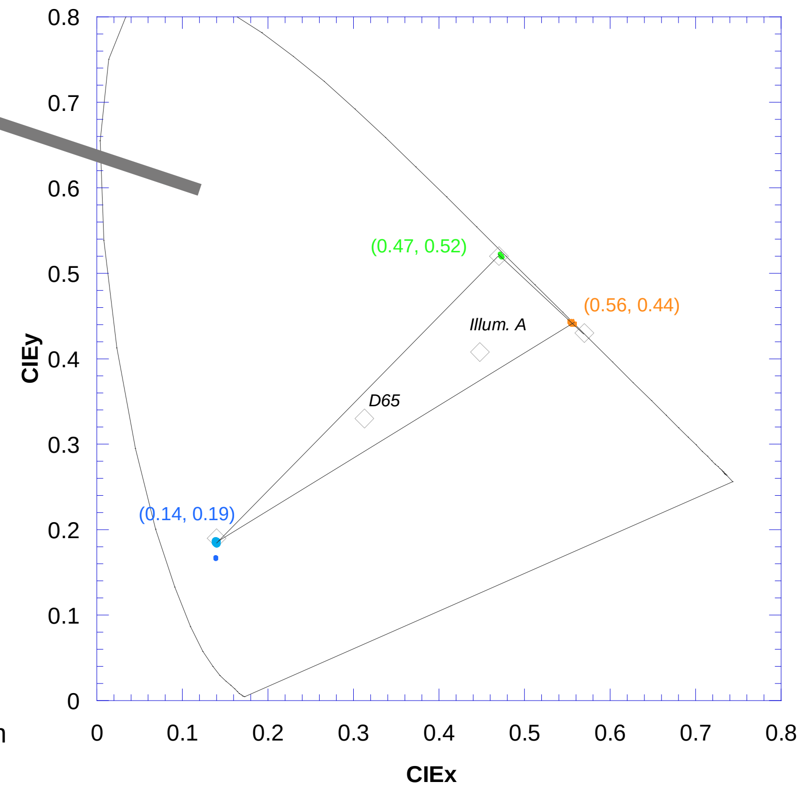
| DISPLAY COLORS | CIE | Lm/W with OE | EQE (%) with OE | Cd/A with OE |
|---|---|---|---|---|
| **Red** | (0.645, 0.354) | **10** | **17** | **22.1** |
| **Green** | (0.266, 0.629) | **12** | **6** | **23** |
| **Deep Blue** | (0.140, 0.140) | **3** | **4** | **6.2** |

These give a combined performance of **8 lm/W** @ 1,000 nits for white (illum. A)




| LIGHTING COLORS | CIE | Lm/W with OE | EQE (%) with OE | Cd/A with OE |
|---|---|---|---|---|
| **Orange** | (0.56, 0.44) | **33** | **20%** | **57** |
| **Yellow** | (0.47, 0.52) | **55** | **22%** | **78** |
| **Pale Blue** | (0.14, 0.19) | **5** | **6%** | **10** |

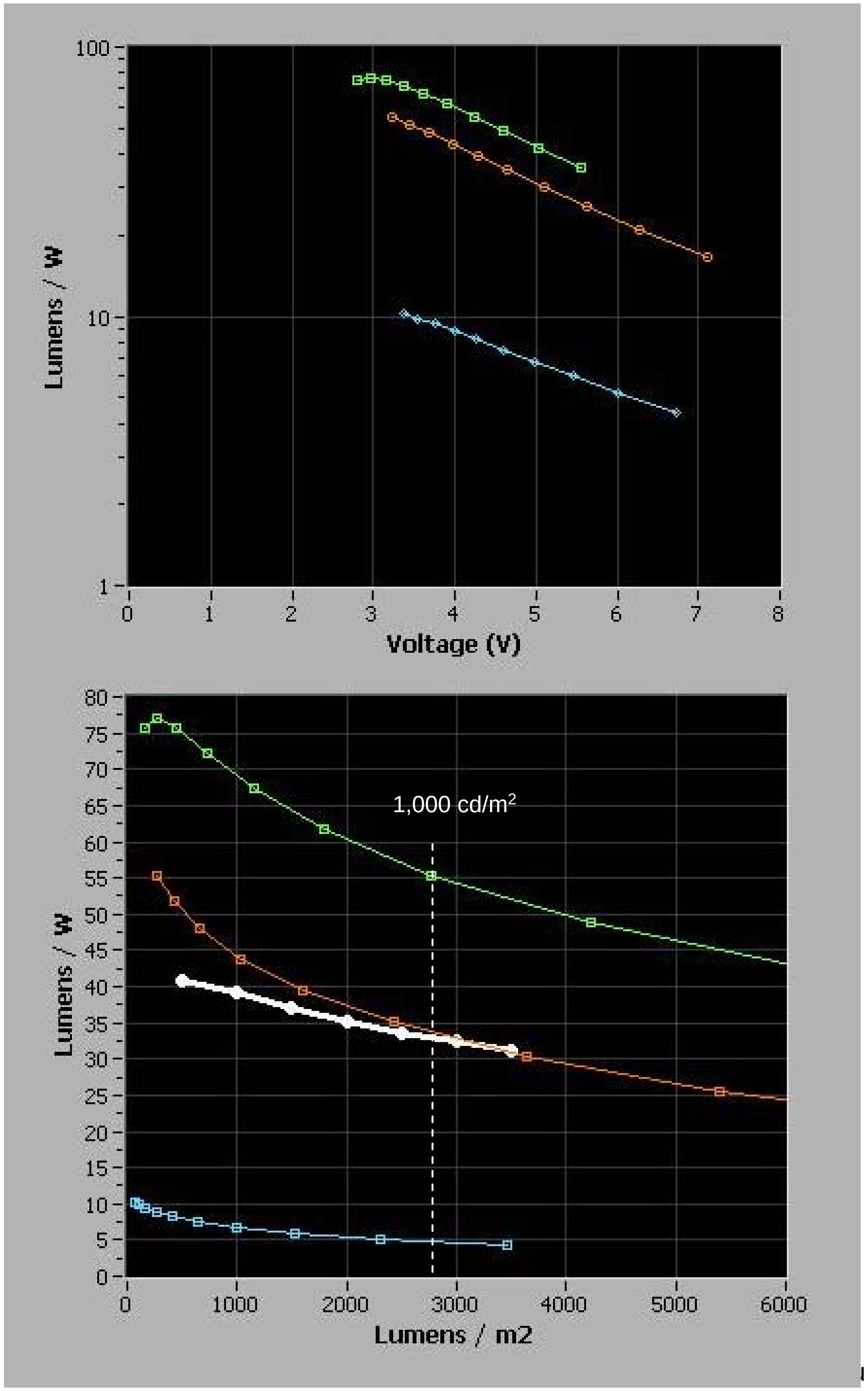
Whereas these give a combined performance of **> 30 lm/W** @ 1,000 nits (illum. A)

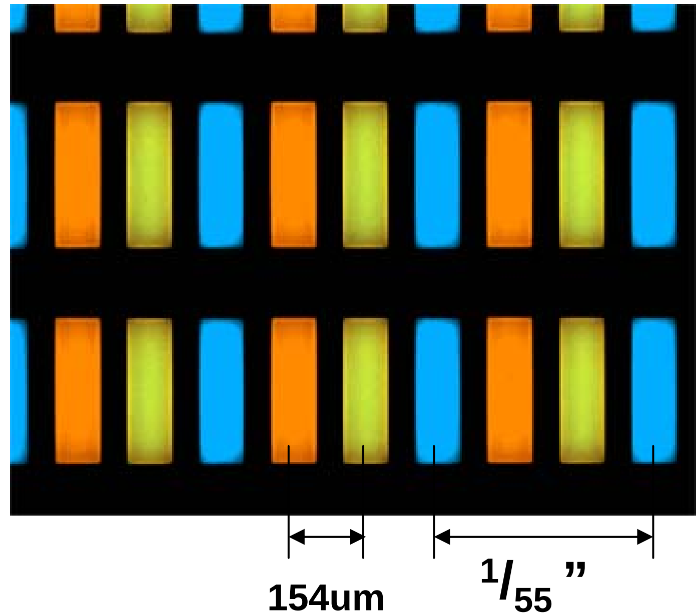



These data are for solution-processed devices with an EML printed in air. Emissive area is 50 $cm^2$

All data are quoted at 1,000 $cd/m^2$ and include an outcoupling enhancement film (OE)

# Choice of Materials Set is Important

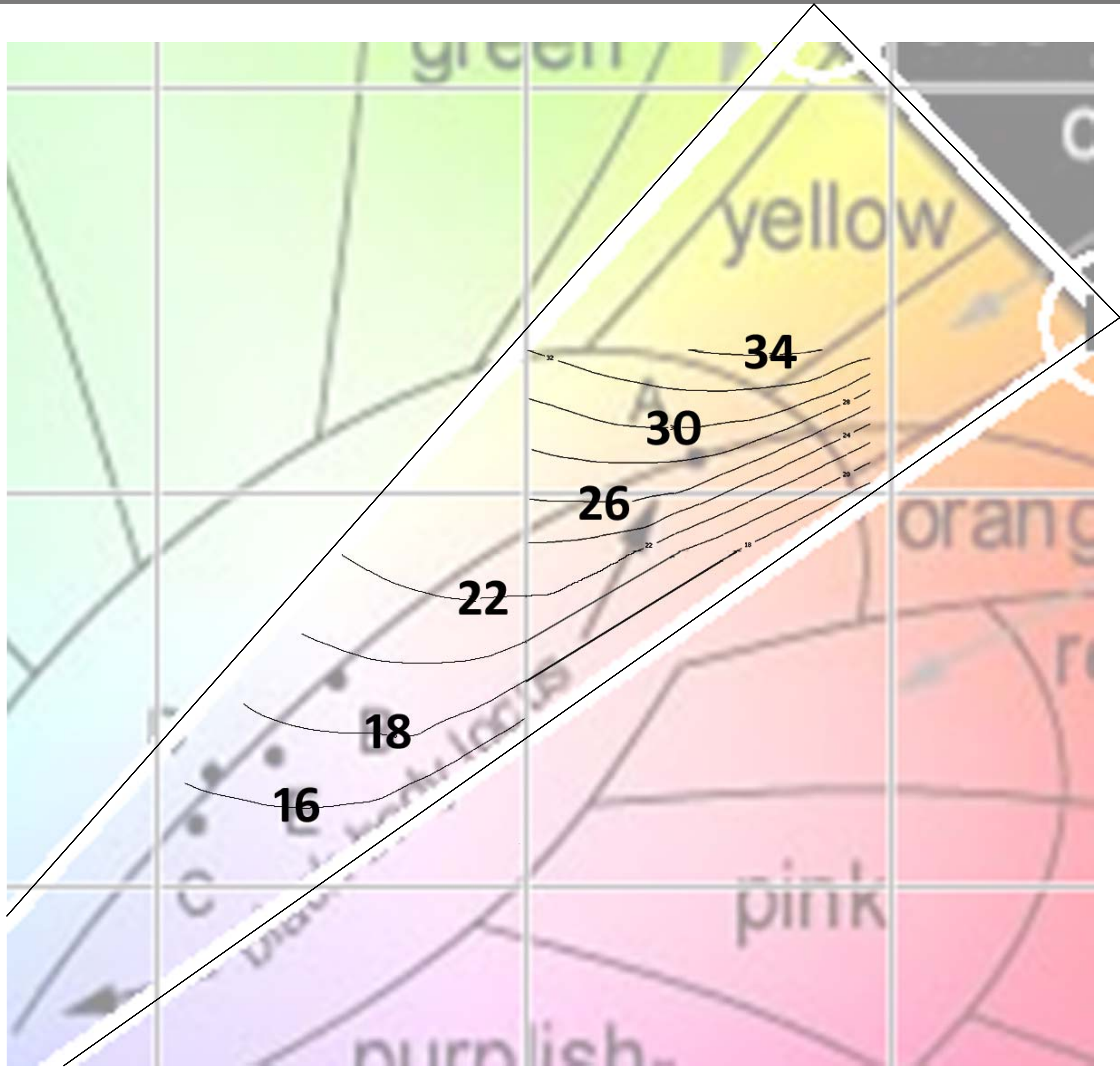


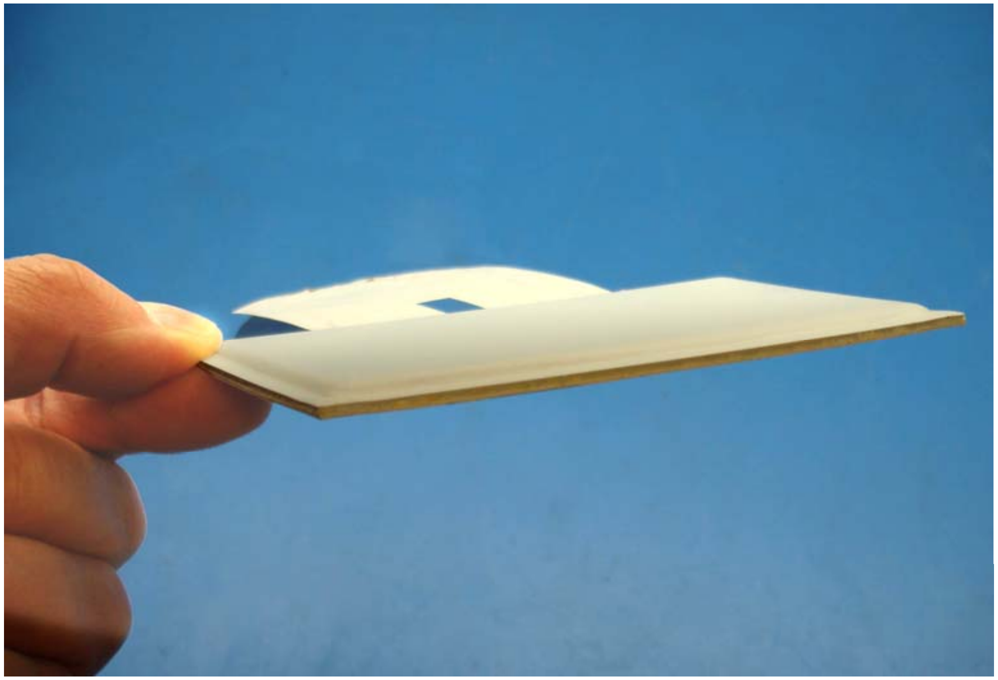




Orange – Yellow – Pale Blue combination showing the individual performance, and the combined performance of **> 30 lm/W** @ 1,000 nits (illum. A)

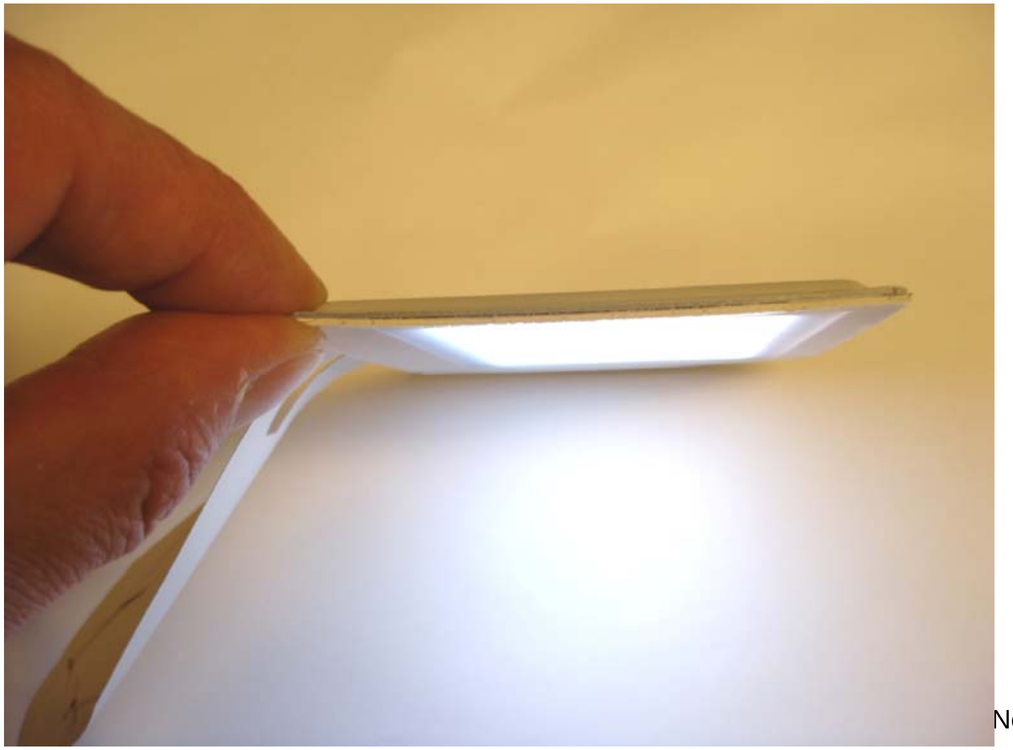
The 3 ‘primary’ colors can be individually controlled to give a color-tunable device.

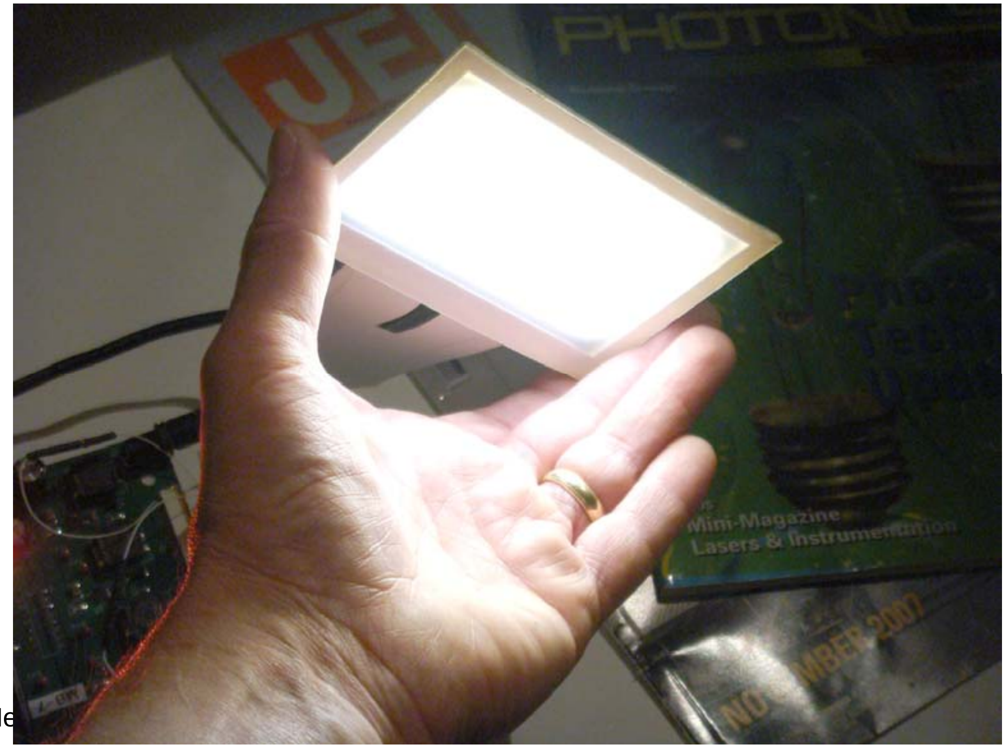
This plot shows the lm/W contours of these devices, for ‘whites’ of various color temperatures.





50 cm$^2$ emissive area, 4.3 mm thick



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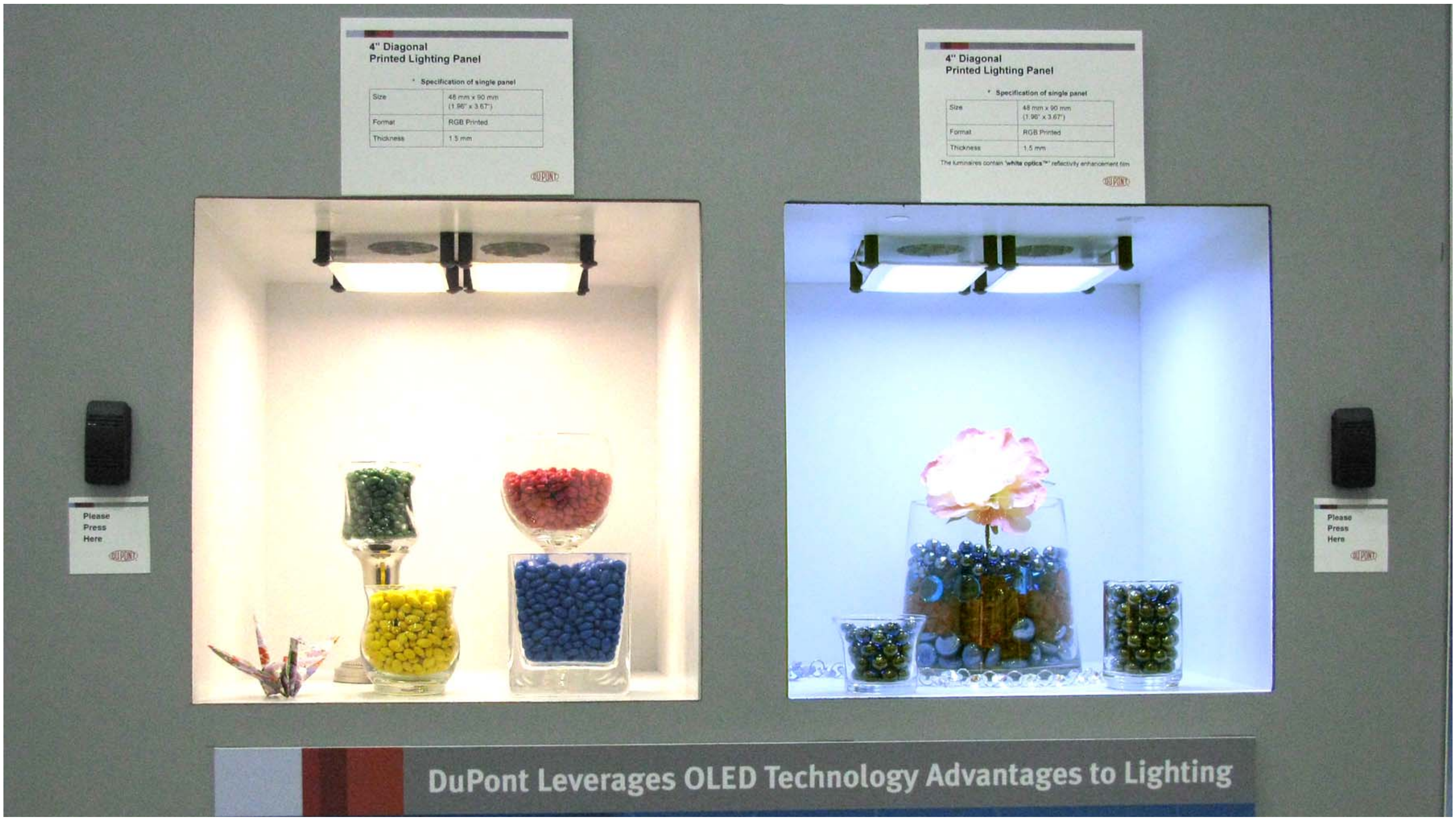
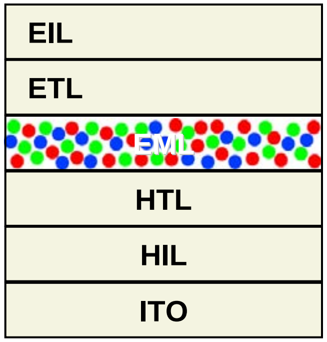
2 luminaires were fitted into each light box.

Each panel was running 1,500 – 2,000 nits

Visitors could scroll through a range of colors:  2700K white, 6500K white, or the O-Y-B primaries.



# Materials Development for GE R2R Process




**DuPont focus:**
•Long lifetime high efficiency emitters, especially blue
•High triplet energy HTL to prevent blue quenching
•A common host for blue, green, and red dopants

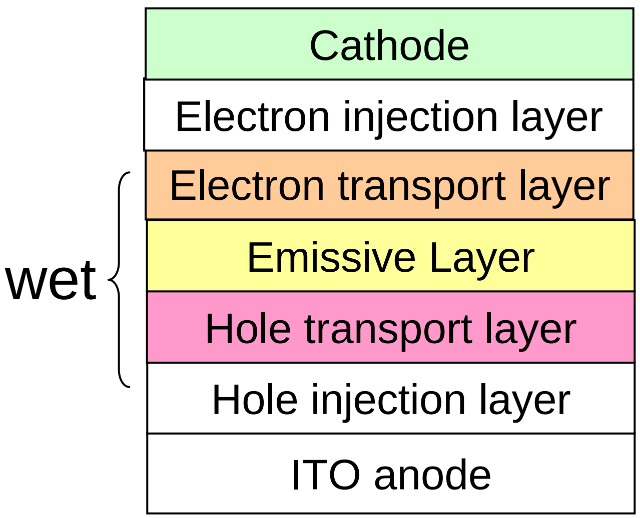
It is expected that DuPont will deliver many iterations of materials modifications based on GE and internal testing and feedback which will occur throughout the program.

**So far we've found that**
•DuPont green and red emitters developed for displays can be used in GE's process.
•HIL formulation was modified for GE's process
•Status (no outcoupling enhancement):

| CRI | CCT | $\Delta$BB | PE, lm/W | EQE, % | V, V |
|---|---|---|---|---|---|
| 88 | 3395 | 0.03 | 24.5 | 15.4 | 4.4 |

# 2010 Wet-Coated Green/Red OLEDs

- All 4 organic layers wet-coated
- Metal-based small-molecule OLEDs




| | T70 (hrs) | T50 (hrs) |
|---|---|---|
| **Red** | 55,000 | ~130,000 |
| **Green** | ~170,000 | ~300,000 |

Wet-coated OLEDs can have LED-like lifetime

DOE SSL (DE-EE-0003250) (2010-2012)

# Conclusions

Through our work on AMOLED displays, we developed a strong level of competency in process and materials development for solution-coated OLED devices.

We are beginning to apply this knowledge to the development of materials for OLED solid-state lighting.

Our approach is based upon reduction in total cost of ownership (manufacturing and maintenance) through the use of solution-processing techniques and simplified device architecture.