OLED Manufacturing Challenges

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2021 DOE Lighting R&D Workshop

OLEDWorks Leading the OLED Lighting Revolution

Industry Leader

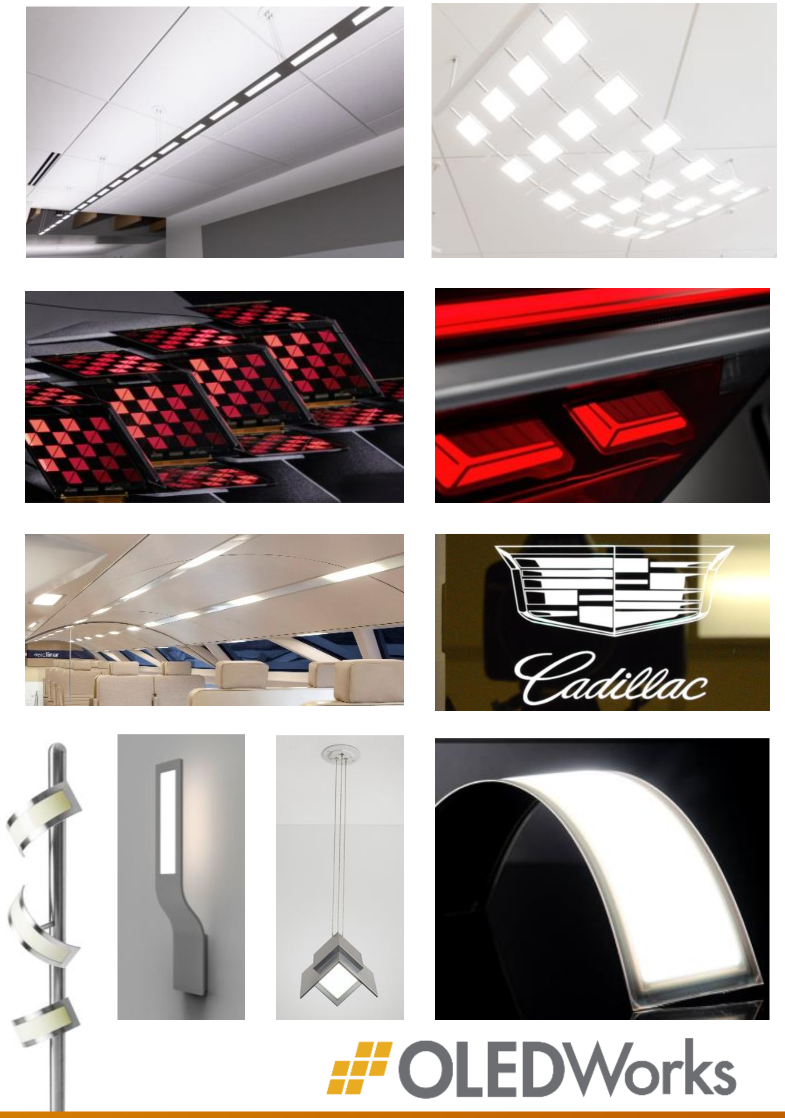
- **Team** – Combination of world leading OLED experts from Kodak and Philips, founded in 2010
- **Technology** – Over 180 patents, critical trade secrets and know-how
- **Manufacturing** – Multiple manufacturing facilities (Aachen, Germany and Rochester, NY USA)
- **Performance** – Highest performing commercial products in the world

Multiple Market Segments

- **General & Specialty Lighting**
  - Acuity Brands Lighting to exclusively use OLEDWorks' OLED Light Engines
  - Over 25 additional luminaire manufacturer partnerships
  - Collaboration with Corning to enable bendable OLED lighting based on Willow glass
- **Automotive & Embedded Lighting** – Collaboration announced with Audi
- **Micro-display** – High-performance OLED micro-displays in development for consumer, commercial and military products

State-of-the-Art Manufacturing and Development

- Aachen high volume manufacturing line for automotive and general lighting products
- Rochester R&D tools and flexible manufacturing line for prototyping and specialty products
- Quality: ISO 9001, ISO 14001, ISO 45001 certified, Full traceability via a factory MES system
- IATF 16949 automotive certification qualification in process



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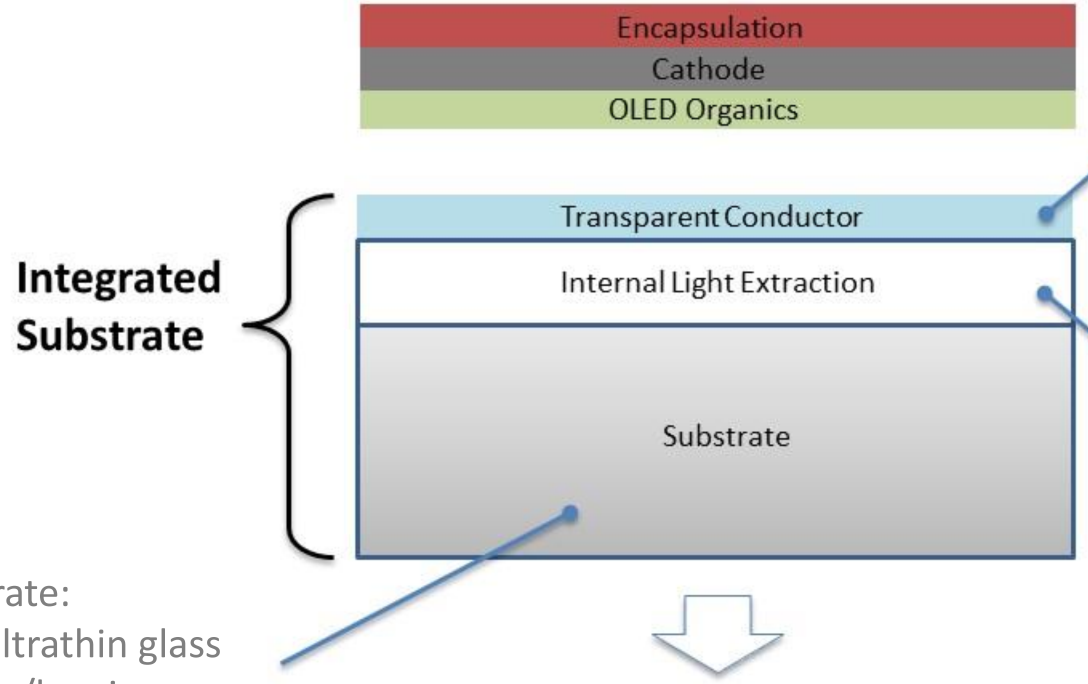
Integrated OLED Substrates

What is an integrated substrate?



Transparent conductor (TC) – serves as anode electrode for BE OLED:

- Indium Tin Oxide (ITO)
- ITO + metal grids
- AgNWs, CNTs, other
- Conductive polymer
- Metal film

Internal light extraction (ILE):

- Inorganic frit glass – no patterning necessary
- Organic polymer based:
  - Scattering type, buried MLA, corrugation, etc.
  - Requires patterning

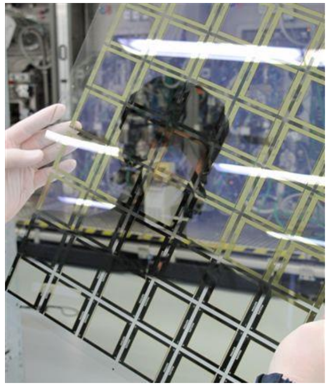
Base substrate:

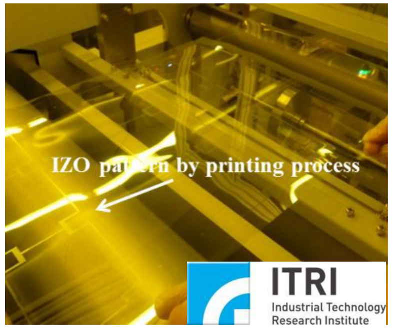
- Glass, ultrathin glass
- Plastic w/barrier
- Metal foil (TE only)

Integrated Substrate Manufacturing

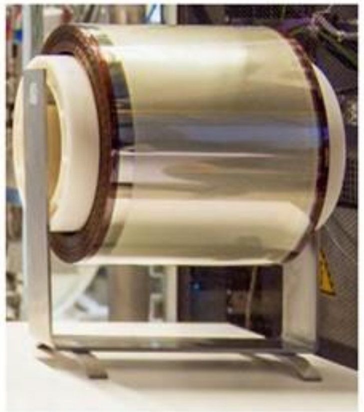
How to reduce high cost of integrated substrates?

Opportunity	Challenges
Near term cost reduction for G2/2.5 rigid integrated substrates: < $100/m^2$	• Integrated substrate cost largely dependent on volume • Most ITO suppliers located in Asia – high shipping costs • Most ITO suppliers do not have printing capability for light extraction layer (ILE) or alternate transparent conductors (TCs)
Scale rigid substrate size from G2/2.5 to G4/5: < $60/m^2$	• Supply of G4/5 integrated substrates lacking • Excessive shipping costs - need to locate raw glass and integrated substrate production line near OLED production line
Roll-to-roll (R2R) flexible glass substrate production for higher throughput: < $40/m^2$	• Moderate capital investment – locate R2R substrate production line near OLED production line • Defect detection and quality control • Process integration & patterning challenges • Need flexible, printable internal light extraction technology





ITO-Coated Willow Glass

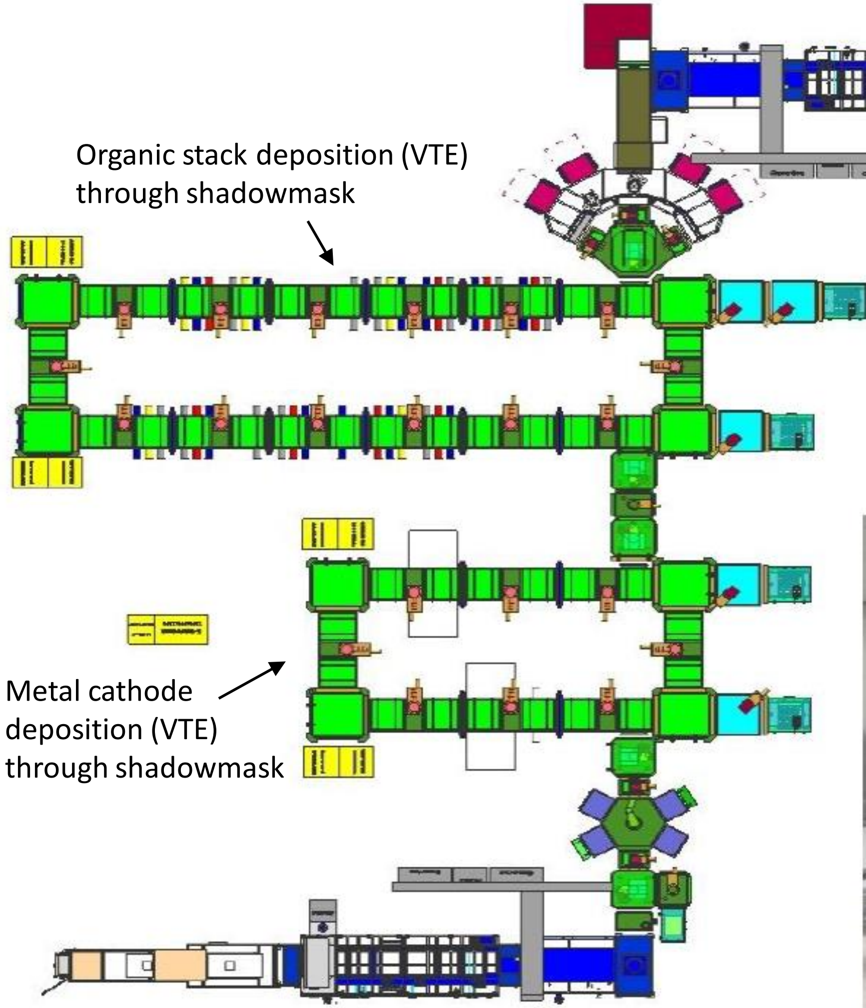


Width - 330 mm
Length - 100 m

CORNING VON ARDENNE Fraunhofer FEP

OLED Production Line

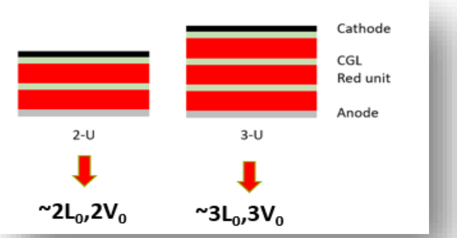
U. Hoffman, CIOS 2015



G2.5 production line capable of 2-6 stack OLEDs with 40+ organic layers

Ag Cathode
PH R+G unit
CGL
FL B unit
CGL
PH R+G unit
CGL
PH R+G unit
CGL
FL B unit
CGL
PH R+G unit
ITO
Internal Extraction Layer
Glass
Scattering foil

J. Spindler, M. Kondakova, et al. SID 2018



M. Kondakova et al. SID 2020

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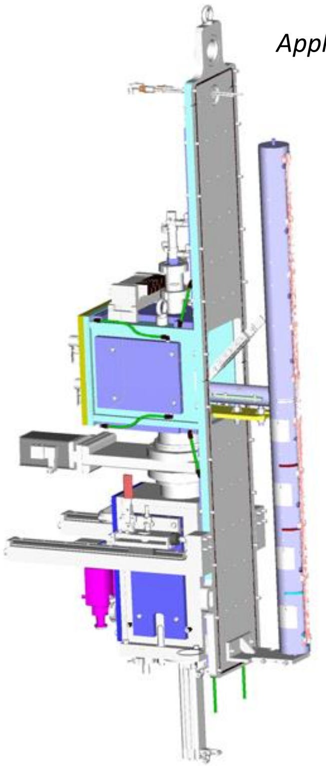
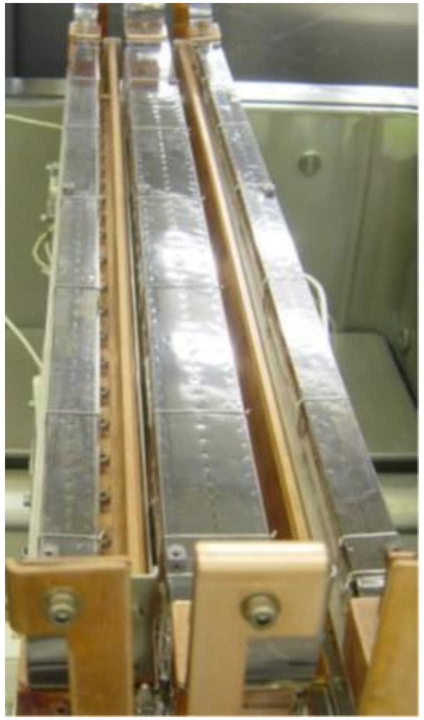
Organic Deposition by VTE (Vacuum Thermal Evaporation)

Early organic linear sources



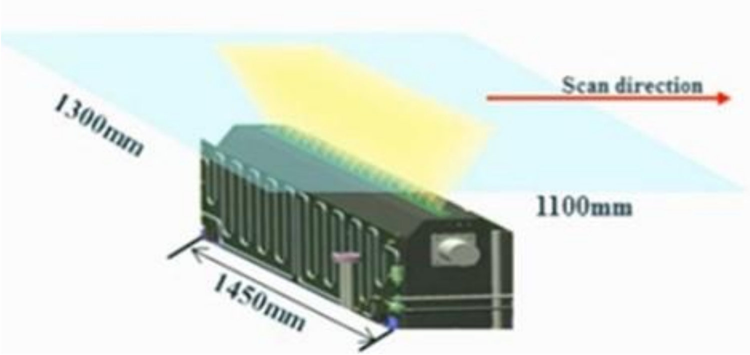
Applied Materials (SID 2010)

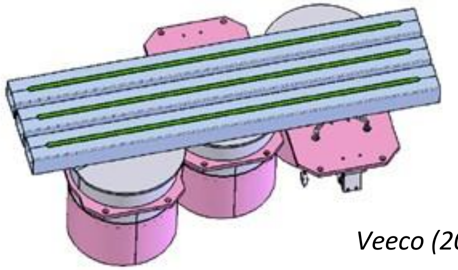
Kodak (2002)



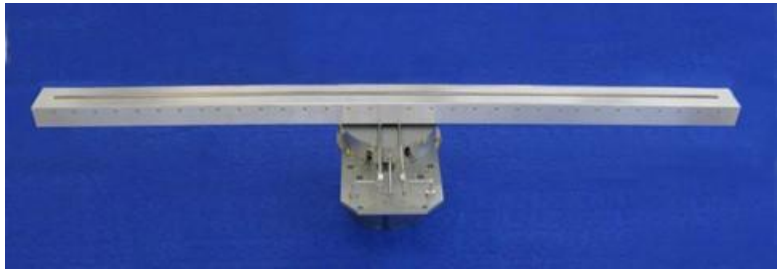
ULVAC (2004)

Sunic System (SID 2013)





Veeco (2010)



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OLED Manufacturing Yield

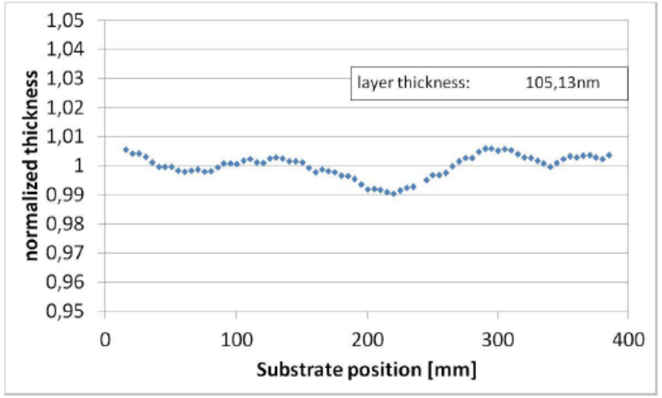
OLED VTE Systems can meet performance requirements for high yield:

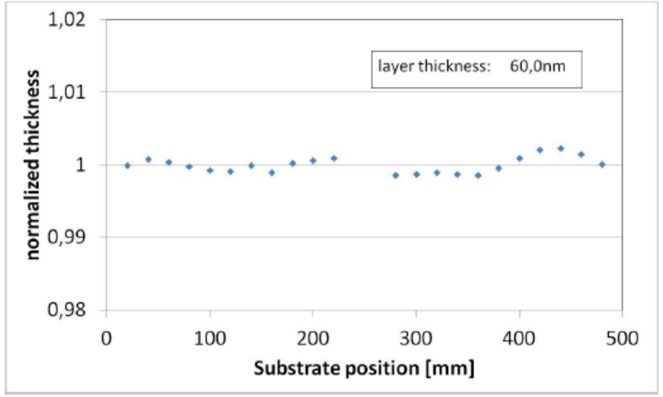
- Film thickness uniformity +/- 1% within sheet, +/- 2% over 10 day run
- Color point consistency within 2-step MacAdam ellipse
- Material utilization > 60%

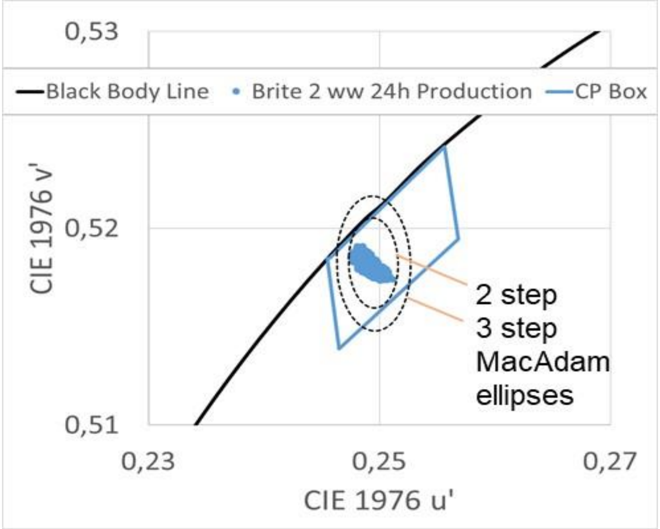
Layer thickness uniformity:

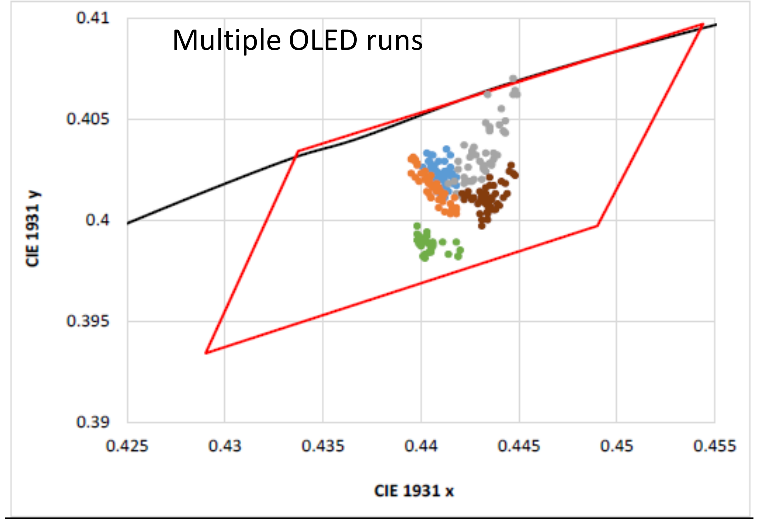
Perpendicular transport direction: ± 1 %
(This is given by source design)

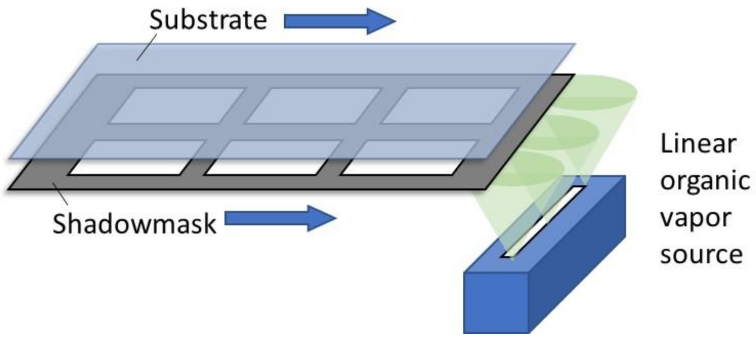
in transport direction : < ± 1 %
(This is given by constant speed)







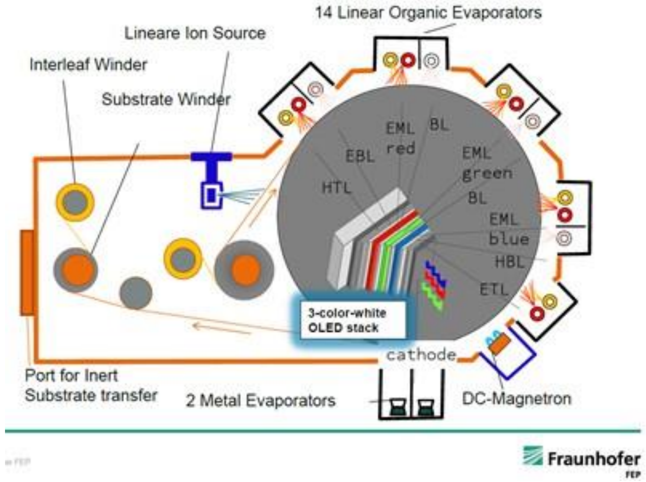




VTE Opportunities & Challenges

Opportunity	Challenges
Increase throughput by reducing TACT time from 2-3 min to < 1 min	• Higher evaporation rates – organic materials must not degrade at higher temperatures • Manage thermal load to substrate
Scale VTE system from G2/2.5 to G4/5	• Large capital investment • Need market demand to justify
Higher throughput roll-to-roll (R2R) VTE system	• Moderate capital investment with lots of risk • Need supply of integrated flexible substrates • Many integration & web handling challenges

Sunic G5 OLED System



FEP / Von Ardenne R2R VTE System

ITRI R2R VTE System

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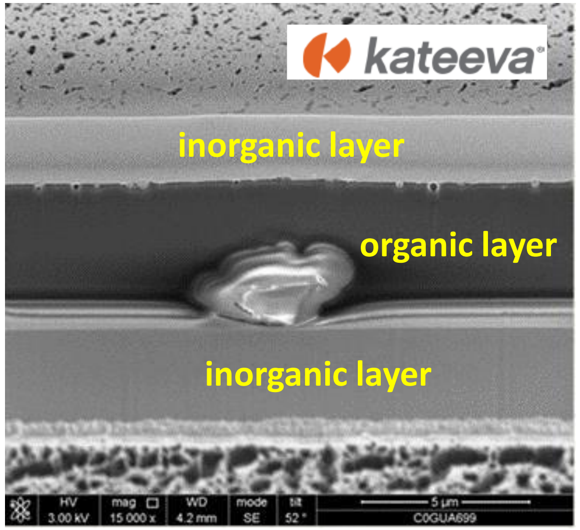
Thin Film Encapsulation (TFE)

Requirements:
- Meets product lifetime expectations (10-20 yrs) and accelerated lifetime test requirements (>1000h @ 85C/85%RH for General Lighting and >5000h for Automotive)
- Thermally and mechanically stable, low stress
- Pinhole free, conformal and tolerant of particles
- Long term reliability – no cracking, defect formation
- Inexpensive to manufacture and scale
- Ability to be patterned or removed from contacts
- Flexible, compatible with R2R processing

Current status: Alternating inorganic/organic layers
- Inorganic films by PECVD – high maintenance and scaling cost
- Organic layers by printing – requires change from vacuum to N_2 environment



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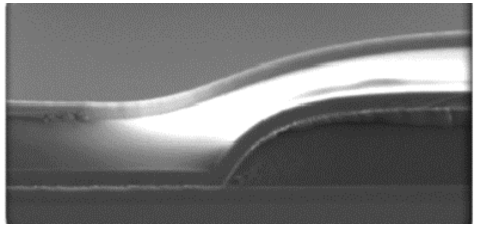
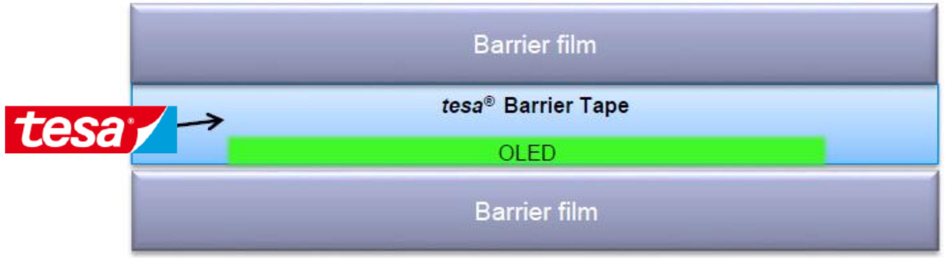
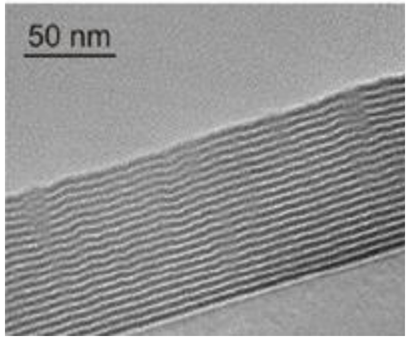
Emerging TFE Solutions

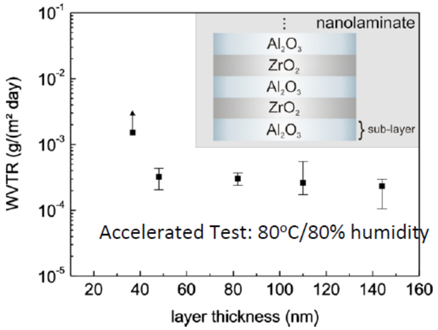
Opportunity	Challenges
Multi-layer PECVD (no organics)	• Still high costs of PECVD • Decoupling of particle defects
All-ALD nanolaminates or ALD/PECVD hybrid (no organics)	• Decoupling of particles with thin inorganic films • Film stress and cracking with bending • ALD relatively slow process
Film type encapsulation: barrier foil adhered to OLED with moisture-absorbing adhesive	• Vacuum lamination without trapping air or moisture • Handling/storage of barrier film to avoid moisture absorption • Edge quality of cut films

AKT Applied Materials, SID 2018









Veeco / Cambridge Nanotech

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Backend Finishing – Rigid OLEDs

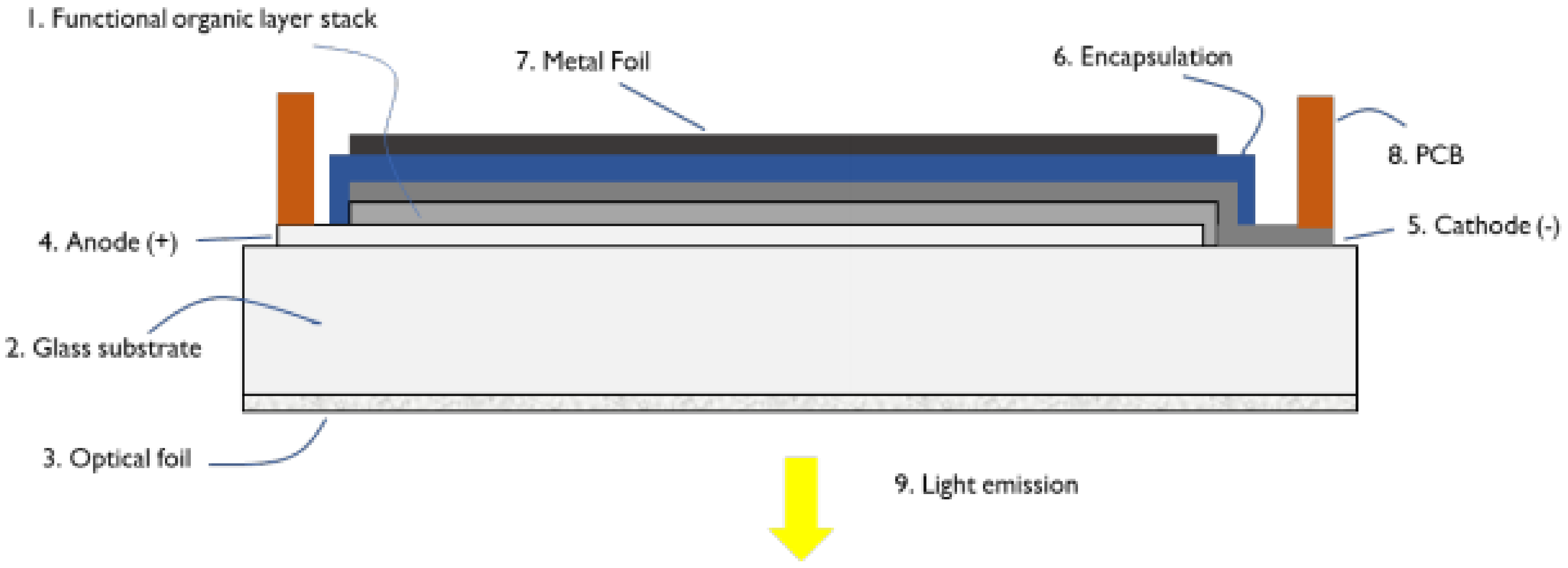

Figure 1: Schematic of Brite 3 Panel, Level 1

- Technology focus has been on substrates, electrodes, organics, encapsulation and light extraction
- Other components add significant cost (~33%): heat spreading, electrical connection

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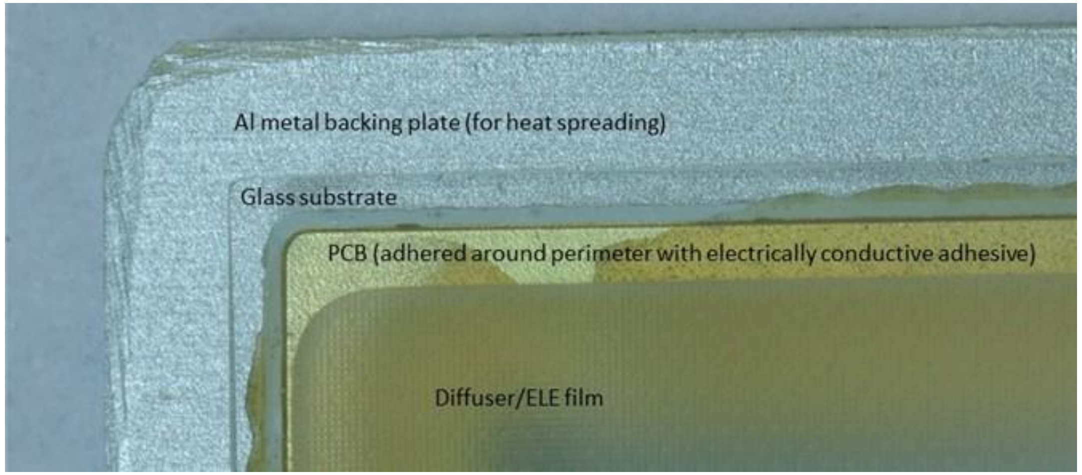
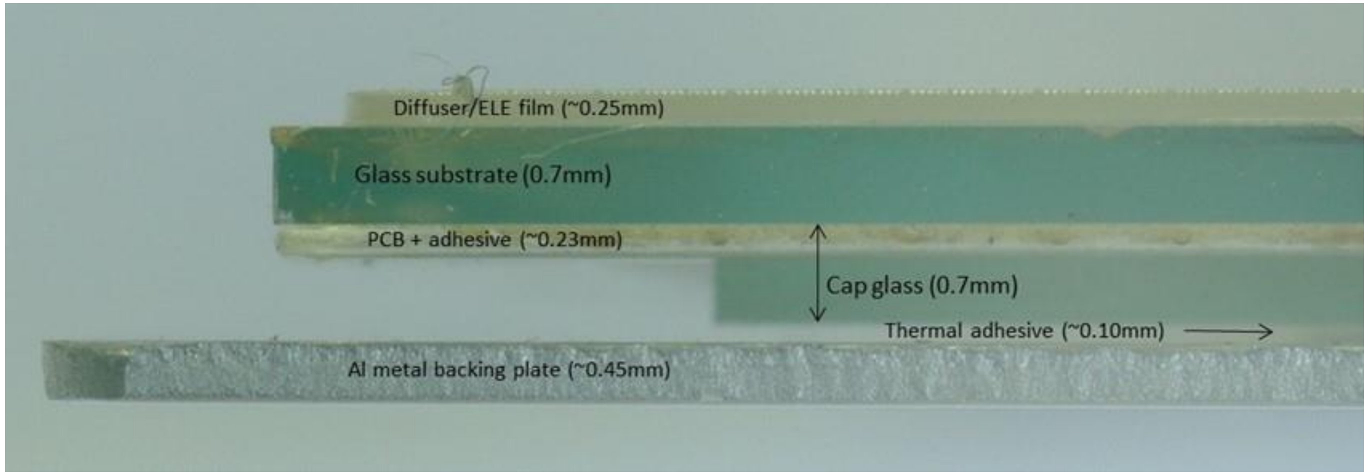
Backend Finishing – Rigid OLEDs



Competitor's OLED panel structure



- Metal foil for heat spreading and encapsulation protection
- Perimeter PCB for uniformity and electrical connection of panel to drivers
- Optional metal backing plate (level 2 finish) for mechanical support and mounting options plus additional heat spreading
- Wires for external connection to driver

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Backend Finishing – Bendable OLEDs

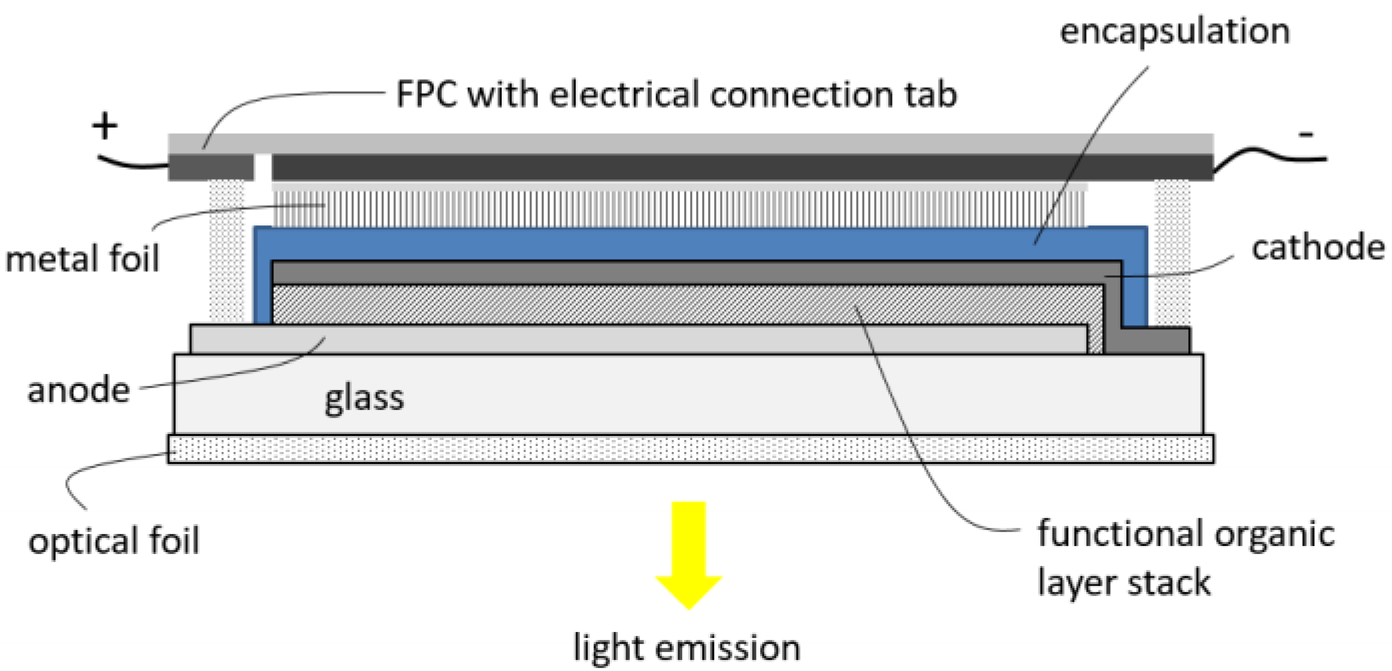
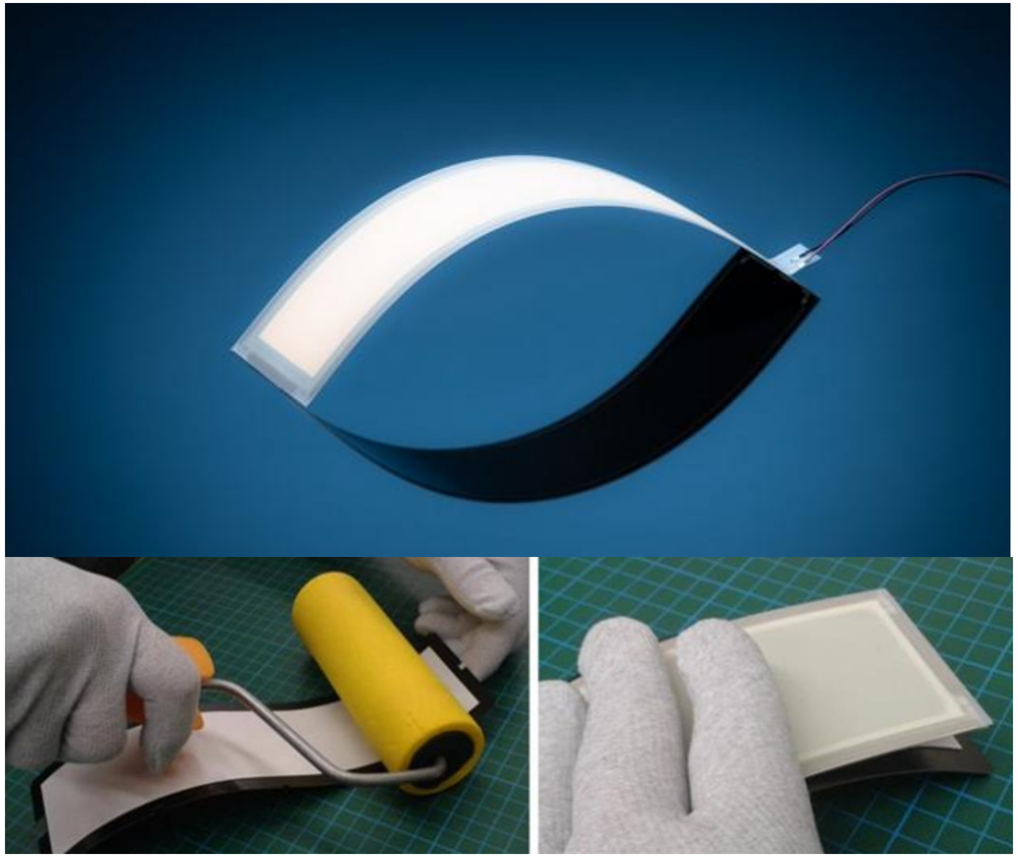
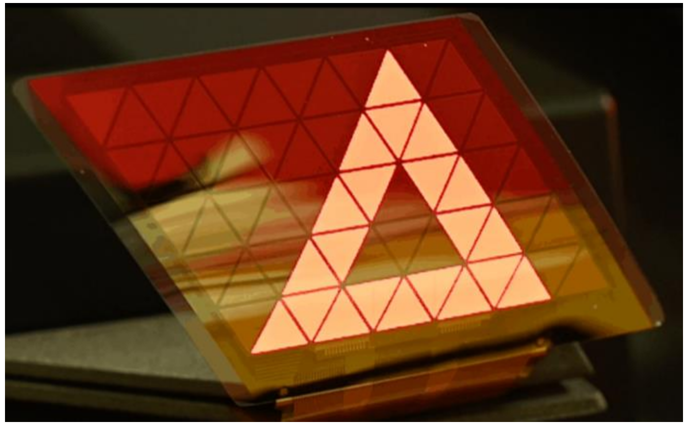


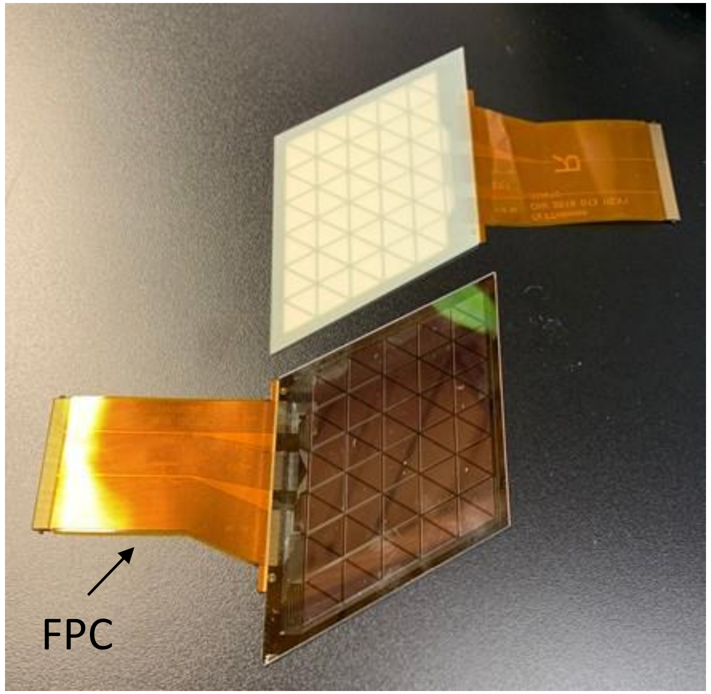
Figure 1 - schematic illustration of the LumiCurve Wave



- Still needs heat spreading metal foil
- Still needs perimeter contacting for uniformity and electrical connection of panel to drivers, but requires FPC, not PCB
- Additional need to protect bendable glass edges and surfaces with oversized films/foils
- Additional need to mount panel onto rigid support to maintain curvature and for mechanical support

Automotive and Segmented OLEDs





- Automotive panels include metallization on the substrate and flexible printed circuit (FPC) for electrical connection
- FPC connects to PCB containing driving electronics for control of individual lit segments, like a display
- Mirror-like ‘chrome’ finish – no light extraction films

OLED Yield Considerations

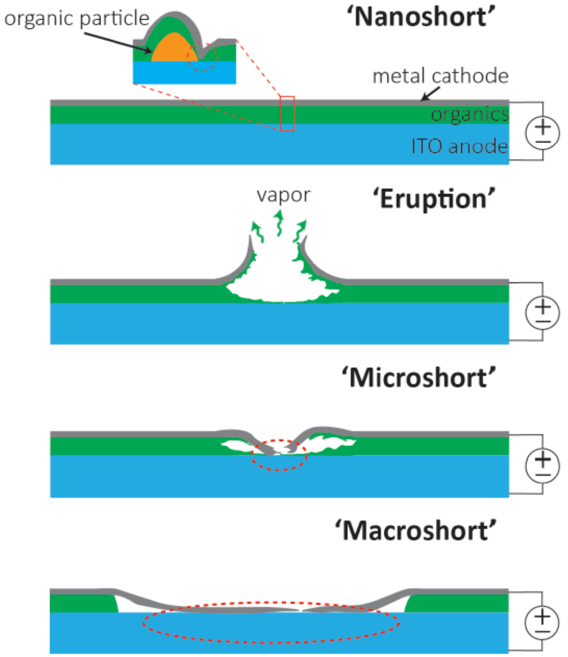
OLEDs are large area devices > 100cm^2 which are susceptible to particle defects and electrical leakage/shorts due to thin (~0.5um) organic stack separating electrodes.

Techniques for yield improvement:

- Short tolerant structures and techniques
- Smooth surfaces <5-10nm RMS, no abrupt changes in height
- Thicker organic stacks
- Routine cleaning of OLED deposition chamber, masks, etc.
- Electrical short reduction techniques
- Fuse-like layers, thin dielectric layers

High yield > 80% is achievable now, but continuous improvement needed to achieve > 95% for both rigid and bendable OLEDs

Key stages in the lifecycle of short



PSU DOE Project "Nature of Catastrophic Shorts in OLED Lighting", N. Giebink et al

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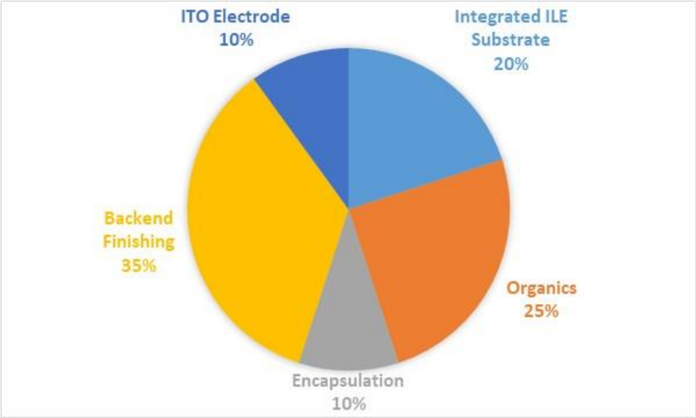
Summary

- Manufacturing of OLED displays has matured and achieved economies of scale with Gen 10+ factories being commissioned in Asia
- OLED lighting manufacturing still has the opportunity for lower cost manufacturing facilities using R2R or combined R2R/R2S
- Cost reduction important for market expansion, especially for general lighting
- Lower cost solutions needed in several areas:
  - Backend finishing – simplified materials and process
  - Integrated substrates – light extraction, electrodes
  - Organics – reduced # of stacks, better utilization
  - Encapsulation – lower cost solutions

OLED BOM breakdown



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