The Challenge of R2R Manufacturing of OLED Lighting for General Lighting Market

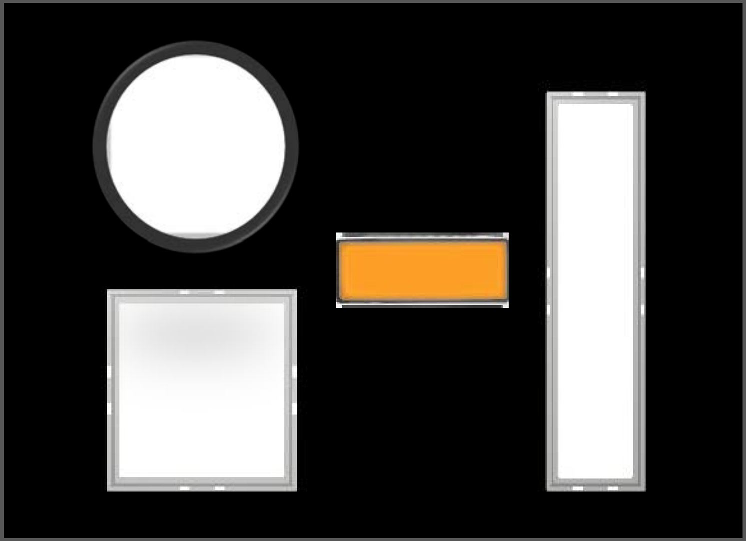
John Hamer, COO

January 30, 2018 – DOE SSL R&E Workshop Nashville Tennessee

OLEDWorks introduction

- 2010: OLEDWorks established by former members of the Eastman Kodak Company OLED team
- 2014: Corning®/OLEDWorks exclusive JDA for bendable OLED lighting panels
- 2015: Acquisition of Philips OLED business
- State-of-the-Art Manufacturing in U.S. and Germany (20k m^2 capacity, scalable to 120k m^2)
- World's highest brightness, longest lifetime, highest quality OLED lighting panels
- Quality: ISO 9001, ISO 14001, OHSAS 18001 certified, Full traceability via a factory MES system

Brite portfolio



- High brightness white >8,000cd/m^2
- New shape – round
- Warm white and neutral white
- Improved efficacy 80lm/W
- Excellent light quality CRI >90, R9 >50
- Lifetime at high brightness >30,000 hours

Market introduction of a bendable OLED on thin glass

Corning® Willow® Glass (*0.1mm thick*) combines the best attributes of Glass and Film substrates

	Glass	Plastic Film
Benefits	• High-Temp Processing • Optical Performance • Ultimate barrier • Performance / Lifetime equal to rigid	• Best fit for R2R Manufacturing process • Ease of Installation and Use • Full flexibility
Shortcomings	• Defects on surfaces and edges limit maximum stress and radius of curvature • Bending/twisting in 2D results in breakage	• **Barrier properties** • Performance / Lifetime

Corning® Willow® Glass combines the best of Glass and Film

Design Challenges of Flexible Glass OLED Structures

Typical Structure

- Careful engineering and design required to make the OLED product robust to handling
- Selection of materials and thicknesses is critical to control stress and strain in each layer
- The design of the location of neutral axis during bending is important
- Protection of glass surfaces and glass edges is required to prevent damage which weaken the glass

Motivation for Curved and Bendable OLED Lighting

Prototypes in testing

- OLED lighting is currently higher priced than LED, and needs to achieve higher sales volumes to significantly reduce costs.
- Unique selling points – OLED lighting can be bendable, flexible, thinner, lighter than LED – allowing more creative designs.
- We target the large general lighting market offering a new value proposition above rigid OLED's and general applications in SSL which will further distinguish OLED lighting from conventional light sources.
- Well suited for new applications in automotive and the integration of OLED lighting in materials

Depreciation

- Gen 5 OLED Lighting Machine - $125M Capital Cost – more including all equip.
- Depreciation is a very large part of the COGS – 25-35%
- Successful large-volume businesses have COGS near BOM cost
- Today's OLED coating speeds are in 5-10mm/sec range
- The table shows 30 sec TAC on Gen 6 (1.5x1.8m) = 60mm/sec ~6-12x current rates
- The problem is that the equipment is still not productive enough
- Higher throughput needed – larger glass area (display model) or **higher transport speed**
- **For more than 10x higher speed without particles → we need R2R processing**

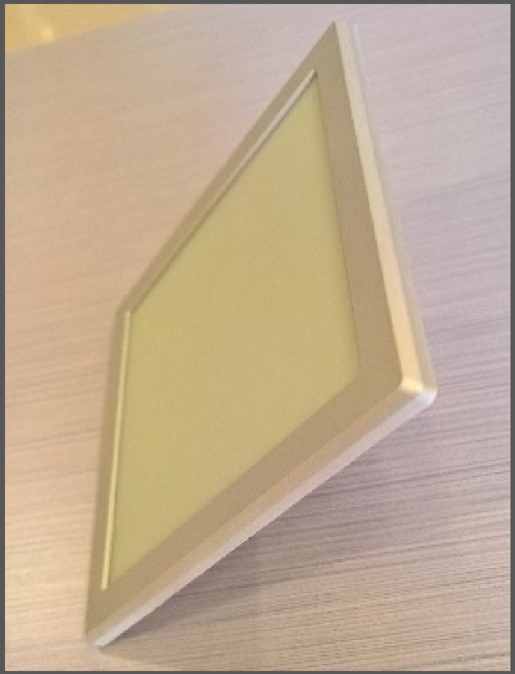
Table 5.4 Cost Targets for Panels Produced by Traditional Methods

	2016	2018	2020	2025
Substrate Area (m^2)	0.2	1.2	1.2	2.7
Capital Cost ($M)	50	125	125	200
Cycle Time (minutes)	3	2	1	0.5
Capacity (1000 m^2/yr)	17	175	350	2,400
Depreciation ($/$m^2$)	600	140	70	35
Organic Materials ($/$m^2$)	150	100	50	15
Inorganic Materials ($/$m^2$)	200	140	100	30
Labor ($/$m^2$)	100	25	15	5
Other Fixed Costs ($/$m^2$)	50	15	10	5
Total (unyielded) ($/$m^2$)	1,100	420	245	90
Yield of Good Product (%)	70	80	85	90
Total Cost ($/$m^2$)	1,570	525	290	100
Deprec % of COGS	38%	27%	24%	35%

From – "Solid-State Lighting 2017 Suggested Research Topics Supplement: Technology and Market Context" by US DOE EERE, September 2017", page 113

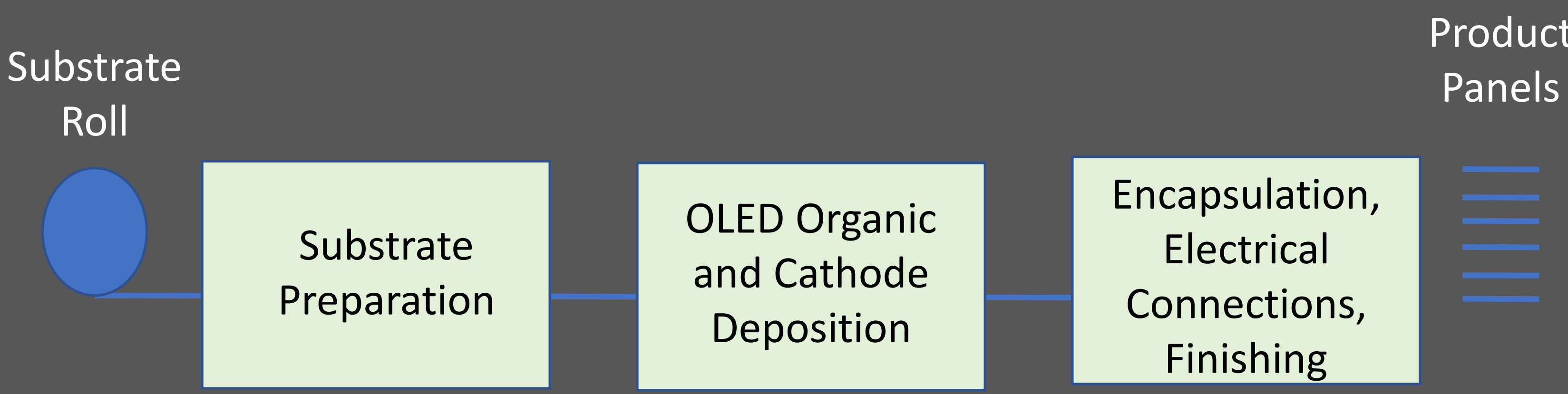
Enabling OLED Lighting to Compete in General Lighting

- For OLED lighting to compete in general lighting, the Cost of Goods Sold (COGS) must be $100/m2.
  - I think it must be lower than this to realize the potential volumes.
- Example of Roll to Roll operation:
  - Kodak made photographic film at 200'/min (1,000mm/sec)
    - Film making required approx 25 liquid layers deposited in 3 coating stations
  - Kodak could never have made film at low-cost if it were done by sheet-to-sheet.



Simple Single Panel Fixture with Brite 2 OLED Panel

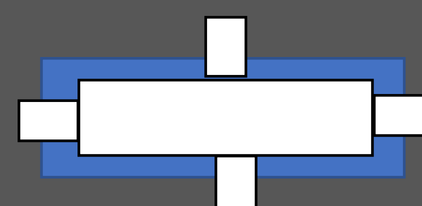
Industrial challenges of R2R OLED manufacturing



Problems to be Solved to Enable R2R VTE of OLED Lighting – Goal > 100 mm/sec

1. Masking – we must eliminate the need for masking

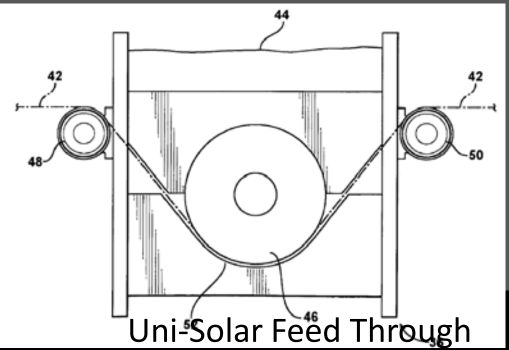
- 2 masks are used today:
  - Organic masks to prevent OLED organic from depositing the seal area and cathode contact area
  - Cathode masks to prevent the cathode from depositing across to the anode contact area.
- Typical spec:
  - Product size (typical 250 mm * 70mm), tolerance **of ±0.5 mm (trend to improve)**
  - **No front touch**
- OLEDWorks has a DOE project to develop a technology solution
  - We have a poster on this project in the poster session.



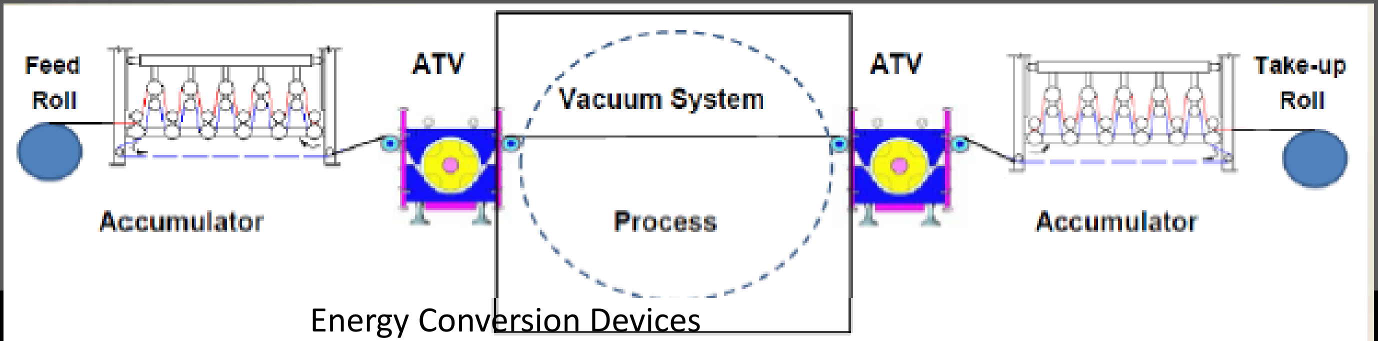
OLEDWorks Naturally Illuminating

Problems to be Solved to Enable R2R VTE of OLED Lighting – Goal > 100 mm/sec

2. Web handing the at start and end of the line – choices:
   a. Feeding web into vacuum with only front side contact
      - Splices must pass through the feed-through
   b. Making splices in vacuum – can't stop the web, therefore need to spice on fly, no front side contact therefore no storage elevator for web in vacuum.



Uni-Solar Feed Through



Energy Conversion Devices

OLEDWorks Naturally Illuminating

Problems to be Solved to Enable R2R VTE of OLED Lighting – Goal > 100 mm/sec

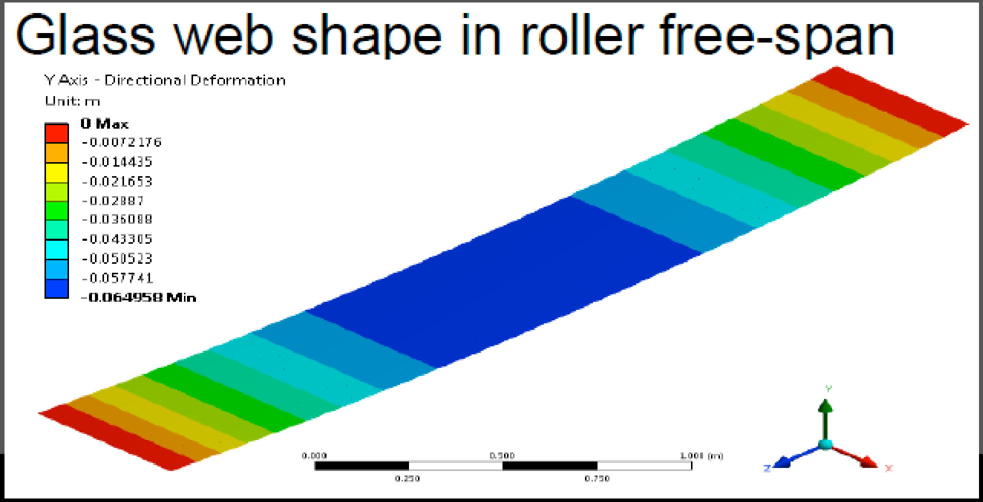
3. Other issues in web handling at start and end of vacuum section:
   - Drying of the web before start
   - Rollup of web without damage to substrate, OLED, or encapsulation

Corning Glass, Sue Lewis, Proflex Conf, Nov 2017

OLEDWorks Naturally Illuminating

Problems to be Solved to Enable R2R VTE of OLED Lighting – Goal > 100 mm/sec

4. Handling web in deposition section of vacuum coater – ~40 layers, 40m?
   - Tension in web, preventing tear-offs in machine - transport on support belt?
     - Perhaps develop depo down with particle control or technology for insensitivity to particles (prevent shorting and defects in encapsulation)



Corning Glass, Sue Lewis, Proflex Conf, Nov 2017

OLEDWorks Naturally Illuminating

Problems to be Solved to Enable R2R VTE of OLED Lighting – Goal > 100 mm/sec

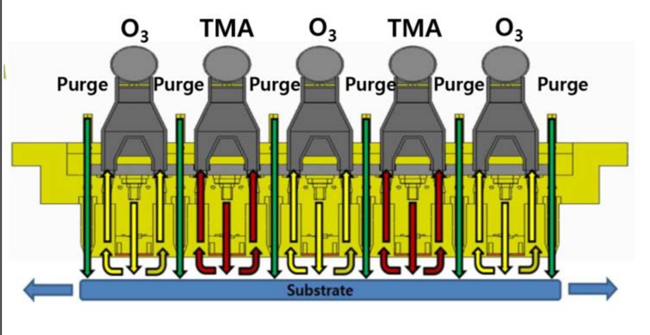
5. High-Rate Evaporation
   - Evaporate without decomposition
     - Novel vapor generation – like from aerosols (Mike Long of Aixtron)
     - Methods to limit time that materials are at elevated temperature (replenishment/feeding methods)
   - Stable machine operation – methods to monitor and control vapor generation rate – Pirani, optical methods
6. High Rate Condensation
   - Look at changes to morphology, smoothness in film at very high rates
   - Redesign of particular molecules that limit machine speed.

Sunic 1.3m wide organic evaporation nozzles

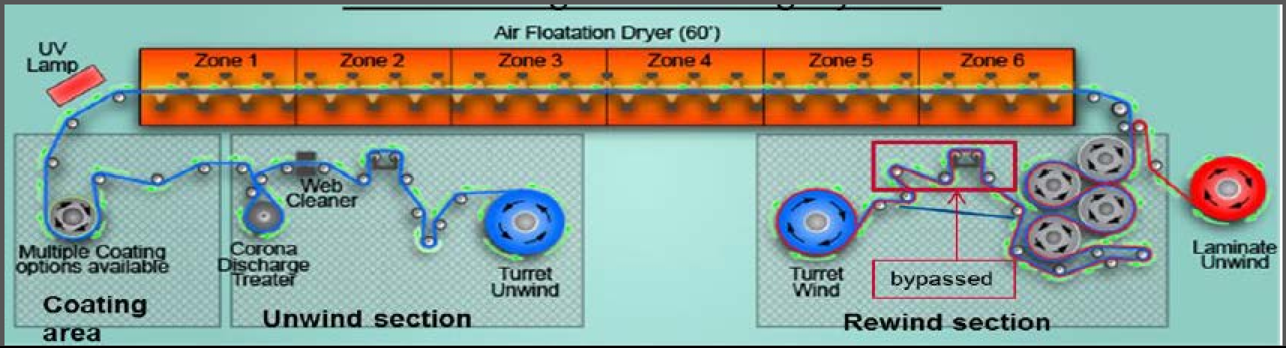
OLEDWorks Naturally Illuminating

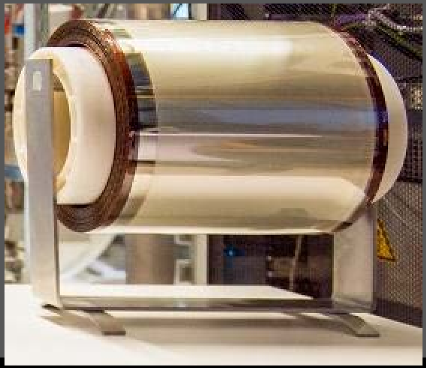
Problems to be Solved to Enable R2R VTE of OLED Lighting – Goal > 100 mm/sec

7. High speed R2R encapsulation
    - In line or off line?
    - Roll to Roll or cut sheet?
        - Spatial ALD?
8. High speed R2R substrate preparation patterned with anode, insulator, and internal light extraction



INVENIA Spatial ALD





60 m thin glass coating and drying machine – Sue Lewis, Corning

Proposal - US Development of R2R Technology for Low-Cost OLED Lighting Production

- Goal – Retain OLED lighting manufacturing in USA by technology advantage that gives a cost advantage.
  - Fraunhofer in Germany has built a pilot machine for VTE OLED
  - LG has constructed a Gen 5 Sheet-to-Sheet machine for OLED lighting in Gumi
    - China is proposing additional several similar machines.
  - Konica Minolta has built a R2R machine for OLED lighting (not in production yet)

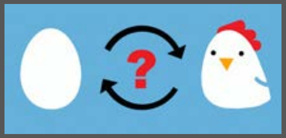
Fraunhofer FEP

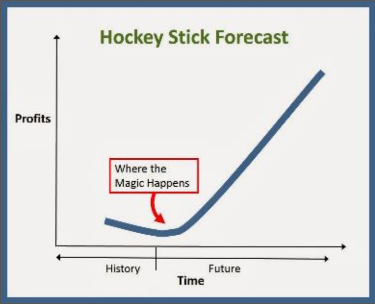
Discussion Points:

- **We propose that the US focus on developing the R2R manufacturing technology to leapfrog to lower-cost manufacturing, and use it for production in the USA.**
- **Now is the time to develop the required technologies**
- **We could leverage existing R2R pilot facilities in the US**

Summary

- The market introduction of bendable products will start this year
- General Lighting is a commodity business and requires commodity pricing
- I predict that OLED lighting will be made R2R within 10 years
    - Commodity pricing requires mature world class mass manufacturing @ lowest cost
    - Chicken and egg (Cost down vs. volume ramp up)
- OLED lighting can achieve the commodity pricing goals through R2R process development and production.   We should keep OLED lighting production in the US.





Thank you