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 m² capacity, scalable to 120k m²)
- 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 $>8,000\text{cd/m}^2$
- 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

**Benefits**

**Glass**
- High-Temp Processing
- Optical Performance
- Ultimate barrier
- Performance / Lifetime equal to rigid

**Plastic Film**
- Best fit for R2R Manufacturing process
- Ease of Installation and Use
- Full flexibility

**Shortcomings**

**Glass**
- Defects on surfaces and edges limit maximum stress and radius of curvature
- Bending/twisting in 2D results in breakage

**Plastic Film**
- **Barrier properties**
- Performance / Lifetime

Corning® Willow® Glass combines the best of Glass and Film
Design Challenges of Flexible Glass OLED Structures

- 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

• 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

<table>
<thead>
<tr>
<th></th>
<th>2016</th>
<th>2018</th>
<th>2020</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate Area (m²)</td>
<td>0.2</td>
<td>1.2</td>
<td>1.2</td>
<td>2.7</td>
</tr>
<tr>
<td>Capital Cost ($M)</td>
<td>50</td>
<td>125</td>
<td>125</td>
<td>200</td>
</tr>
<tr>
<td>Cycle Time (minutes)</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Capacity (1000 m²/yr)</td>
<td>17</td>
<td>175</td>
<td>350</td>
<td>2,400</td>
</tr>
<tr>
<td>Depreciation ($/m²)</td>
<td>600</td>
<td>140</td>
<td>70</td>
<td>35</td>
</tr>
<tr>
<td>Organic Materials ($/m²)</td>
<td>150</td>
<td>100</td>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>Inorganic Materials ($/m²)</td>
<td>200</td>
<td>140</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>Labor ($/m²)</td>
<td>100</td>
<td>25</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>Other Fixed Costs ($/m²)</td>
<td>50</td>
<td>15</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Total (unyielded) ($/m²)</td>
<td>1,100</td>
<td>420</td>
<td>245</td>
<td>90</td>
</tr>
<tr>
<td>Yield of Good Product (%)</td>
<td>70</td>
<td>80</td>
<td>85</td>
<td>90</td>
</tr>
<tr>
<td>Total Cost ($/m²)</td>
<td>1,570</td>
<td>525</td>
<td>290</td>
<td>100</td>
</tr>
</tbody>
</table>

Deprec % of COGS | 38% | 27% | 24% | 35%

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.
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.
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 splice on fly, no front side contact therefore no storage elevator for web in vacuum.
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
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)

Jan 30, 2018
DOE SSL R&D Workshop, Nashville TN
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.
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
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)

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