Innovative High-Performance Deposition Technology for Low-Cost Manufacturing of OLED Lighting

Progress Review

John W. Hamer
OLEDWorks LLC
OLEDWorks
Introduction

• We are the only US manufacturer of OLED lighting panels.
• Founded in Rochester NY in 2010
• 22 full-time OLED experts
  – Over 200 years of combined OLED experience
  – Experience across all areas of OLED technology
• Built a state of the art OLED R&D lab
• Designed and started-up a novel, flexible, scalable OLED production facility.
• We have commercialized our first product.
• We work with many partners:
  – Suppliers to the OLED lighting industry
  – Downstream luminaire partners.
Innovative High-Performance Deposition Technology for Low-Cost Manufacturing of OLED Lighting

• For our novel approach to vaporization, control, and distribution of organic vapor, the project encompasses:
  – Design of the production-scale equipment of the deposition equipment,
  – Testing, analysis, and improvement of the equipment,
  – Implementation into production with demonstration

• The goals of this deposition system are:
  1. Improve material usage efficiency
  2. Improve deposition rate – higher throughput
  3. Lead to lower capital cost OLED deposition machines
  4. Enable use of thermally sensitive materials
## Reference Machines

- The most common OLED lighting system in production/pilot today is Sunic G2 – 370x470mm
  - E.g. LG Chem, First O-Lite, COMMED
  - This is the largest publicly disclosed production machine in use today (370x470mm)
- Future system – G5 - 1100x1300mm

### Approximate Parameters

<table>
<thead>
<tr>
<th></th>
<th>Gen 2 Baseline</th>
<th>Gen 5 Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Size</td>
<td>370x470 mm</td>
<td>1100x1300 mm</td>
</tr>
<tr>
<td>Material usage</td>
<td>15-25%</td>
<td>60%</td>
</tr>
<tr>
<td>TAC time</td>
<td>2-6 min</td>
<td>1-2 min</td>
</tr>
<tr>
<td>Substrate Velocity</td>
<td>1.3-4 mm/sec</td>
<td>9-18 mm/sec</td>
</tr>
<tr>
<td>Operating Time between loading</td>
<td>6 days</td>
<td>6 days</td>
</tr>
<tr>
<td>Area of Good product</td>
<td>8,000-12,000 m2/year</td>
<td>190,000-380,000 m2/year</td>
</tr>
<tr>
<td>Estimated Capital Cost of Whole line</td>
<td>$50-100M (use $75M)</td>
<td>$150-300M (use $200M)</td>
</tr>
<tr>
<td>Depreciation per unit of production</td>
<td>$600-1900/m2</td>
<td>$100-200/m2</td>
</tr>
</tbody>
</table>

### Standard Assumptions:
- 80% uptime, 80% yield, 80% glass usage efficiency
- 5 year straight line depreciation
Project Targets in Terms of Reference Machines

<table>
<thead>
<tr>
<th></th>
<th>Gen 2 Baseline</th>
<th>Gen 5 Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Size</td>
<td>370x470 mm</td>
<td>1100x1300 mm</td>
</tr>
<tr>
<td>Material usage</td>
<td>15-25%</td>
<td>60%</td>
</tr>
<tr>
<td>TAC time</td>
<td>2-6 min</td>
<td>1-2 min</td>
</tr>
<tr>
<td>Substrate Velocity</td>
<td>1.3-4 mm/sec</td>
<td>9-18 mm/sec</td>
</tr>
<tr>
<td>Operating Time</td>
<td>6 days</td>
<td>6 days</td>
</tr>
<tr>
<td>Area of Good product</td>
<td>8,000-12,000 m²/year</td>
<td>190,000-380,000 m²/year</td>
</tr>
<tr>
<td>Estimated Capital Cost of Whole line</td>
<td>$50-100M (use $75M)</td>
<td>$150-300M (use $200M)</td>
</tr>
<tr>
<td>Depreciation per unit of production</td>
<td>$600-1900/m²</td>
<td>$100-200/m²</td>
</tr>
</tbody>
</table>

- The rough goals of the project are to design and build vapor generation and deposition sources to enable:
  - Capital like G2 - $50-100M
  - Material usage like G5 - ~60%
  - Substrate speed like G5 – 9-18 mm/sec
  - Depreciation like G5 - $100-200/m²
  - Easy on heat sensitive materials

- Unfortunately we cannot show the design of our production machine or the design of the new vapor generation and depositions sources.

- However, we will describe the approach, considerations, and progress.
**Motivation – Why this project is important**

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestones</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY10</td>
<td>Panel: &gt;60 lm/W</td>
</tr>
<tr>
<td>FY12</td>
<td>Laboratory Panel: 200 lm/panel; &gt;70 lm/W; &gt;10,000 hours</td>
</tr>
<tr>
<td>FY15</td>
<td>Commercial Panel: &lt;$200/klm (price); &gt;80 lm/W; 25,000 hours; CRI &gt;90</td>
</tr>
</tbody>
</table>
| FY17 | Commercial Panel: $100/klm  
Luminaire: 100 lm/W; CRI >90 |
| FY20 | High-Performance Panel: 160 lm/W  
Luminaire: price <$80/klm; 100 lm/W, 40,000 hours |

Note: Panel size >50 cm²; CCT < 2580-3710K

"Meeting the panel price goal of $200/klm by 2015, or soon thereafter, seems necessary in order to create a large enough demand to justify further investments in R&D and manufacturing capability. The luminaire price goal of $80/klm is appropriate for 2020 if OLEDs are to gain sufficient market penetration to contribute significantly to global energy savings."
Motivation – Why this project is important

Table 1-6 OLED Panel Cost Estimated Progress ($/m²) from Sept ‘13 DOE SSL Mfg Roadmap

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
<th>2013</th>
<th>2016</th>
<th>2020</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated Substrate</td>
<td>500</td>
<td>250</td>
<td>150</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Organic Deposition</td>
<td>1,400</td>
<td>600</td>
<td>250</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>Assembly and Test</td>
<td>600</td>
<td>350</td>
<td>200</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>Overhead (incl labor)</td>
<td>500</td>
<td>300</td>
<td>100</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Total (unyielded)</td>
<td>3,000</td>
<td>1,500</td>
<td>700</td>
<td>180</td>
<td>80</td>
</tr>
<tr>
<td>Yield of Good Product (%)</td>
<td>15%</td>
<td>25%</td>
<td>70%</td>
<td>75%</td>
<td>80%</td>
</tr>
<tr>
<td>Total Cost</td>
<td>20,000</td>
<td>6,000</td>
<td>1,000</td>
<td>240</td>
<td>100</td>
</tr>
<tr>
<td>Deposition Machine Size</td>
<td>G2</td>
<td>G2</td>
<td>G2</td>
<td>G5</td>
<td>G5</td>
</tr>
<tr>
<td>TAC Time (min)</td>
<td>6</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Depreciation (at capacity, after yield)</td>
<td>10,257</td>
<td>6,154</td>
<td>733</td>
<td>222</td>
<td>104</td>
</tr>
<tr>
<td>Total Cost with Depreciation</td>
<td>30,257</td>
<td>12,154</td>
<td>1,733</td>
<td>462</td>
<td>204</td>
</tr>
<tr>
<td>Fraction of Total Cost due to Dep.</td>
<td>34%</td>
<td>51%</td>
<td>42%</td>
<td>48%</td>
<td>51%</td>
</tr>
<tr>
<td>Gross Margins</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Sales Price of Panels</td>
<td>60,514</td>
<td>24,308</td>
<td>3,465</td>
<td>923</td>
<td>408</td>
</tr>
<tr>
<td>Price of light ($/klm at 10klm/m²)</td>
<td>6,051</td>
<td>2,431</td>
<td>347</td>
<td>92</td>
<td>41</td>
</tr>
<tr>
<td>DOE Milestones (2014 DOE MYPP)</td>
<td>200 in FY15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of Luminaire &amp; Channel Costs</td>
<td>4x</td>
<td>4x</td>
<td>4x</td>
<td>4x</td>
<td>4x</td>
</tr>
<tr>
<td>Sales Price of Luminaire</td>
<td>242,055</td>
<td>97,233</td>
<td>13,861</td>
<td>3,694</td>
<td>1,632</td>
</tr>
<tr>
<td>Price of light ($/klm at 10klm/m²)</td>
<td>24,206</td>
<td>9,723</td>
<td>1,386</td>
<td>369</td>
<td>163</td>
</tr>
<tr>
<td>DOE Milestones (2014 DOE MYPP)</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

With the current equipment, we do not hit the DOE milestones for industry success.
Cost and Prices Relative to DOE Targets

Gaps between target price and predicted prices:

- 2015 - ~3-5x
- 2020 - ~4-5x

We need innovation in equipment performance (cost, throughput, flexibility) to help reach the targets.

Cost data is from DOE SSL Mfg Roadmap Sept 2013
Price target data is from DOE SSL MYPP April 2014
Large-Scale Production OLED Deposition Equipment

Vacuum Thermal Evaporation of Organics

- Organic Vapor Generation and deposition sections

Reference Example – Sunic¹ G5 (1100x1300mm)

¹ SID 2013, Paper 55.4 Development of Highly Productive In-line Vacuum Evaporation System for OLED Lighting, J.M. Lim et al
Nozzle Design

• G5 nozzles at 250mm distance achieve 60% material usage efficiency.
• We need to go closer than this to achieve same usage efficiency in less than 1450mm length (Sunic G5 length).
  – The higher the material usage efficiency, the faster the substrate can travel (for a given vapor generation rate)
• To deposit at even higher transport speeds without elevating the evaporation temperature – the nozzle must be design to operate at low pressure.
• We must integrate all of functions into a smaller package
  – Co-deposition of hosts and dopants
  – Widthwise uniformity
  – Thermal management – substrate must stay cool
Deposition of Thermally Sensitive Materials

- Organic materials decompose when held at elevated temperatures for extended times
- To evaporate at high rates,
  - Use large areas for evaporation
    - Careful design of evaporator section to allow higher rates at lower temperatures.
  - Maintain low pressure
    - Careful design of nozzles
    - Careful design of conductances in system
- To extend the lifetime, heat only part of the material at a time.
  - Sunic G5 evaporators can hold up to 2kg of material to permit extended operating time.

<table>
<thead>
<tr>
<th>Material</th>
<th>Test Duration (d)</th>
<th>( T_{\text{evap}} )</th>
<th>+25 K</th>
<th>+50 K</th>
<th>+75 K</th>
<th>+100 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>NET-164</td>
<td>10</td>
<td>227°C</td>
<td>252°C</td>
<td>277°C</td>
<td>302°C</td>
<td>327°C</td>
</tr>
<tr>
<td>SoA ETL</td>
<td>10</td>
<td>293°C</td>
<td>318°C</td>
<td>343°C (no data)</td>
<td>368°C</td>
<td>393°C</td>
</tr>
</tbody>
</table>

Ref “Applying OLEDs in a Manufacturing Process” Information Display, Jan 2014, K. Gilge et al.
Thermal Simulation to Verify of Thermal Uniformity Across a Nozzle Body
Design Methods Used for New Deposition Source - 2

Plume Modeling to Check Coating Cross Track Uniformity vs Position – Simulation of Nozzle Array

![Graph showing deposition thickness vs relative distance from center with and without coating window.](graph.png)
Design Methods Used for New Deposition Source - 3

Deposition Rate vs. Position – necessary for predicting composition uniformity throughout the layers on a moving substrate
Design Methods Used for New Deposition Source - 4

Vacuum engineering to design a system to achieve the desired temperatures and pressures

Pressure in Vaporzier and Deposition System

- Host - existing system
- Host - new system - much higher rate
- Dopant - existing system
- Dopant - new system

Pressure Along Pathway - Arbitrary Units

Scaled Length from Start of Vapor Pathway
Integrated Design of Evaporation and Deposition

• The goal is a synergistic design
  – Smaller system
    • Lower capital cost of evaporator and total machine
    • Closer to substrate
      – Higher material usage efficiency
        » Faster substrate speed
  – Manage pressure and temperature
    • Less stress on materials
      – Higher evaporation rates
        » Faster substrate speeds
    • Less degradation of materials
      – Less downtime for frequent re-loading
        » Higher annual throughput

• All parts work together to achieve remarkable results.
Project Overview

• Phase 1 - First year
  A. Design, build, and test the full scale vaporizer components
  B. Refine design
  C. Design, build, and test single component deposition system in production equipment with vaporizer.

• Phase 2 – Second year
  A. Design, build, and test multi-component evaporation deposition system
  B. Demonstrate performance in production equipment.
Where are we in the project – 7 months

Project Plan
• Phase 1 - First year
  A. Design, build, and test the full scale vaporizer components.

Where are we after 7 months into the project:
• We have completed all design work including
  – Vacuum engineering
  – Thermal modeling
  – Plume shape modeling
• All major components have been fabricated or are being fabricated.
• Assembly will begin later this month.
• We are on schedule and on budget.