Overview of Pixelligent’s OLED Lighting Program

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• DOE SSL Award #DE-EE0006673

• NIST TIP Award #70NANB10H012

• OLEDWorks
Corporate Highlights

- Advanced Materials Company Leveraging Next Generation Nanotechnology
- Solid State Lighting and Optical Components and Films Markets
- State-of-the-Art Labs & Scaled Manufacturing
- $40M Invested in Product Platform
- Global Customer Base
Technology Leader in Nanocrystal Dispersions

- ZrO$_2$ Nanocrystal Dispersions
- Best Dispersions Available
  - High Loadings (>80wt%)
  - 95% Transmittance
  - Narrow Size Distribution (5 nm – 10 nm)
  - High RI (>1.8)
  - Tunable Viscosity
- Highly Scalable Process
- Strong IP Position
Manufacturing Process

Current: 5 Ton Pilot Line

- Nanocrystal Synthesis
- Capping
- Purification and Dispersion

- Compliant with US & Int’l EHS Standards
- Q1 2016: 40 Ton Capacity On Line
Process Stability – PixClear® PA

Mean Particle Size (nm)

Spec: 7 – 10 nm

Optical Density at 400 nm

Spec: OD Less than 0.8

D9999, DLS by intensity

Spec: D9999 Less than 30 nm
PixClear® Nanocomposite Performance

Refractive Index

<table>
<thead>
<tr>
<th>Loading</th>
<th>k</th>
<th>Haze</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 wt%</td>
<td>&lt;10⁻³</td>
<td>0.5%</td>
</tr>
<tr>
<td>80 wt%</td>
<td>&lt;10⁻³</td>
<td>0.5%</td>
</tr>
<tr>
<td>50 wt%</td>
<td>&lt;10⁻³</td>
<td>0.5%</td>
</tr>
<tr>
<td>0 wt%</td>
<td>&lt;10⁻³</td>
<td>0.4%</td>
</tr>
</tbody>
</table>

3 Micron Film in Acrylic Polymer
Measured by J.A. Woollam with VUV-VASE
Measurements on solid films
PixClear® Nanocomposite Performance
Select Partners & Customers

OSRAM
Merck
Cree
Shin-Etsu
Philips
3M
Nichia
LG Chem
OLEDWorks
LG Innotek
Fraunhofer
Lumileds
Saint-Gobain
Solvay
OLED Lighting Challenges & Solutions
OLED Light Extraction Problem

• Total Internal Reflection traps most of the light in the device
• Some light escapes naturally – most needs to be redirected
• Different light extraction schemes vary in how and where light is redirected
• Broad agreement for next commercial products that ITO/Substrate interface is where light should be redirected and that scattering is how light should be redirected
  – Access to most of light
  – Minimal impact to device
  – Most mature manufacturing processes
Scattering Approach

• Scattering is a random process
  – Limited ability to control which light gets scattered and direction of scattering

• Improved light extraction relies on multiple passes through the device
  – Maximize reflection at cathode
  – Minimize absorption
  – Minimize path length through device – enough scattering
Focusing – High Index Lens

- Highest possible efficiency – all light extracted on first pass
- Absorption in device and cathode reflectivity are less important
- Not practical – too expensive and ruins form factor
Focusing - Microlens

- Not a random process but light still makes multiple passes through device
- Absorption in device and cathode reflectivity are less important
- Preserves form factor

Source: Panasonic Built Up Light Extraction Substrate
Pixelligent OLED Lighting Roadmap

- Performance - light extraction vs. $\theta$ and $\lambda$, flexible vs. rigid, control of etendue, uniformity
- Manufacturability - number and cost of manufacturing steps, yield, repeatability
Generation 1

- Condensed Scattering Layer with high index smoothing

- May eliminate need for external light extraction
- Pixelligent recently launched an OLED family of commercial products
Generation 1 Product Launched August

• Formulated nanocomposites
  – High refractive index smoothing layer

and

• Unformulated dispersions
## Summary of High RI Smoothing Layer (Gen 1)

### Performance Criteria

<table>
<thead>
<tr>
<th>Performance Criteria</th>
<th>Performance Targets</th>
<th>Pixelligent ILE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optical Properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refractive Index</td>
<td>&gt; 1.75 – 1.85@ 550 nm</td>
<td>✔</td>
</tr>
<tr>
<td>% Transmittance</td>
<td>&gt; 90% in visible region</td>
<td>✔</td>
</tr>
<tr>
<td><strong>Physical Properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smoothing Surface</td>
<td>Planarize scattering structures on substrate &lt;1 nm Ra</td>
<td>✔</td>
</tr>
<tr>
<td>Compatible With Current Manufacturing Processes</td>
<td>Spin coating, slot die coating, screen printing, vacuum coating process, etc.</td>
<td>✔</td>
</tr>
<tr>
<td><strong>Thermal Stability</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150 C – 250 C 30 min</td>
<td>Maintain High R.I. and High % T</td>
<td>✔</td>
</tr>
<tr>
<td><strong>Chemical Properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compatible with polymers</td>
<td>Maintain uniform, transparent planarizing coatings</td>
<td>✔</td>
</tr>
<tr>
<td>Compatible with scatterers</td>
<td>Maintain uniform, transparent planarizing coatings</td>
<td>✔</td>
</tr>
<tr>
<td>Compatible with chemical processing</td>
<td>Stable to ITO patterning processes, acids, bases, solvents, etc.</td>
<td>✔</td>
</tr>
</tbody>
</table>
Generation 2

- Distributed Scattering Layer with high index layer

 More efficient than condensed scattering layer
 More functional material but simpler manufacturing process than Gen 1
Device Tests

EQE% of White OLED Devices on Slot-Die Coated ILE

<table>
<thead>
<tr>
<th></th>
<th>Control (No IEL)</th>
<th>With Pixelligent IEL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No EEL</td>
<td>EEL</td>
</tr>
<tr>
<td>0 deg</td>
<td>28.1</td>
<td>48.3 1.7X</td>
</tr>
<tr>
<td>Integrate</td>
<td>32.3</td>
<td>46.2 1.4X</td>
</tr>
<tr>
<td>0 deg</td>
<td>56.5 2.0X</td>
<td>57.3 2.0X</td>
</tr>
<tr>
<td>Integrate</td>
<td>67.9 2.1X</td>
<td>61.9 1.9X</td>
</tr>
</tbody>
</table>

Source: OLEDWorks

- The slot-die scattering films passed high pressure water jet cleaning process, ITO deposition process, and OLED manufacturing process.
- The control devices were tri-layer white OLED with color temperature ~ 3000K.
Prototype Gen 2 Formulations Available for Testing

- Nanocomposite plus scatterer
- Tunable viscosity
- Uniform thickness
- Uniform scatterer loading
- Low defect rate
- UV Curable
- Slot-die, spin, or inkjet coating
- Low surface roughness
- NDA required

Scatterers

ZrO$_2$ Nanocrystals

Polymer
Generation 3

- Distributed Scattering Layer with gradient high index layer

- More efficient than distributed scattering layer
- More complex manufacturing process
- Pixelligent currently developing materials and manufacturing processes
Generation 4

- 3-dimensional graded index with or without scatterers
- Highest efficiency
- Offers ability to direct light – non-lambertian
- Most complex manufacturing process
- Subject of Future work
Simple Manufacturing

- Pixelligent Formulation compatible with multiple deposition methods – *slot-die*, spin coat, inkjet, spray coat, ...
- Not dependent on substrate – flexible or rigid, film or glass,
- Pattern with slot-die, inkjet, UV patterning, ...
Light Extraction for OLED Displays

- Display Image Must be Preserved – Avoid Pixel Cross Talk by Putting Lens Close to Pixel, need good alignment
- Different Light Extraction Structures Possible – e.g. Conventional or Fresnel Lens, Many Ways to Optimize
- Lenses preserve polarization to maintain absorption of ambient light – high contrast ratio
Summary

- Pixelligent makes solution processable nanocomposites with tunable properties superior to pure polymers
- High index nanocomposite formulations used to make efficient internal light extraction
- Compatible with a wide variety of OLED manufacturing (and potential manufacturing) processes
- Prototype Gen 2 Formulation now available for testing under NDA

Source: Acuity Brands
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