High Refractive Index Materials in Lighting Applications
2019 SSL R&D Workshop

Dr. Selina Monickam
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Outline

• Company Overview
• High Refractive Index (HRI) Material
• Application of HRI Materials in OLED Lighting
• OLED Device Results
• Conclusion
• Acknowledgements
## Company Overview

<table>
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<tr>
<th>Disruptive Technology</th>
<th>• Technology leader in Next Generation High-RI Nanocomposites</th>
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<tr>
<td>Key Markets Served</td>
<td>• OLED Display, HD Display, OLED Lighting, LED Lighting</td>
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<td>Customers &amp; Partners</td>
<td>• 50+ Leading Device, Advanced Materials, &amp; Consumer Electronics Companies</td>
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<td>Manufacturing</td>
<td>• 5 MT Pilot Baltimore, MD</td>
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<tr>
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<td>• 40 MT Full-scale, PA, 4Q18</td>
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<td>Locations</td>
<td>• Baltimore, MD - HQ</td>
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<td></td>
<td>• Taipei, Taiwan - Sales</td>
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<tr>
<td>Distributors</td>
<td>• Korea, Japan, Taiwan</td>
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High Refractive Index Material (PixClear®)

**ZrO₂ Nanocrystals**
- Uniform 5~10 nm spheres
- High RI
- Transparent
- Not photoactive
- Bandgap ~5.8 eV

**Nanocrystals in polymer matrix**
- Disperse in monomer/oligomers with and without solvent
- High transparency (>80%)
- Low viscosity

**Nanocomposites**
- Molded into HRI structures such as thin films, lenses...
- Solution processable
- Compatible with many different deposition methods
High Refractive Index Nanocomposite

- High RI, High Transmittance, and Smooth Surface

- Wavelength (nm)
  - Refractive Index
    - 400 nm: 1.56
    - 500 nm: 1.60
    - 600 nm: 1.64
    - 700 nm: 1.68
    - 800 nm: 1.72
    - 900 nm: 1.76
    - 1000 nm: 1.80

- %Transmission vs. NC wt% Loading
  - %T_650nm
  - %T_350nm

- Ra = 0.529 nm
- RMS = 0.665 nm
- Rz = 6.455 nm

5 x 5 um scan area
Pixelligent’s HRI Material in OLED Lighting:
- for Internal Light Extraction (ILE) Layer

- High Refractive Index - reduces index mis-match between the ITO and the substrate
- Low surface roughness
  - smoothing layer for scatterers or textured surfaced
  - Binder for suspending scatterer particles
HRI Material for Light Extraction

Developed 2 HRI Formulations

- High Refractive Index Formulation
- High Refractive Index Scatterer Formulation
Light Extraction Structures

Glass/Barrier Film Layer (n=1.5)

High Index Smoothing Layer n = 1.75 – 1.85

Transparent Anode (n=1.8)

OLED

Generation 1

Glass/Barrier Film Layer (n=1.5)

High Index Layer n = 1.75 – 1.85

Transparent Anode (n=1.8)

OLED

Generation 2

Glass/Barrier Film Layer (n=1.5)

1-D Gradient Index Layer

1-D Gradient Index Layer

Transparent Anode (n=1.8)

OLED

Generation 3

Glass/Barrier Film Layer (n=1.5)

3-D Gradient Index Layer

3-D Gradient Index Layer

Transparent Anode (n=1.8)

OLED

Generation 4
OLED Lighting Device with HRI ILE

As high as 2.8X Improvement in Light Extraction in Device with Pixelligent ZrO₂ ILE compared to controls

(Source: OLEDWorks)
OLED Lighting Device with PixClear HRI ILE

Extraction efficiency and Efficacy as a function of Luminance

HRI integrated devices
✓ Uniform extraction efficiency and efficacy
✓ Can achieve ~90 lm/W at 3000 cd/m²

(Source: OLEDWorks)
**OLED Lighting Device with HRI ILE**

HRI integrated devices

- Uniform extraction efficiency over angles
- Much reduced angular color variation (<0.001)
- Much lower voltage at high brightness
- >50,000 hours lifetime based on accelerated tests

(Source: OLEDWorks)
HRI ILE in flexible OLED Lighting Device

Formulation coated on polyimide substrate

HRI integrated devices
✓ Minimal to no change in efficacy after device is bend once around 50 mm radius

(Source: OLEDWorks)
Properties that can improve device efficiency

- Scatterer concentration
- Scatterer size
- Binder RI

(Source: OLEDWorks)
Shown Feasibility

- Working OLED devices
- High extraction efficiency (~50%)
- High lumens (~90 lm/W)
- Uniform efficiency over all angles
- Better angular color uniformity
- Flexibility
- Passed preliminary reliability test

Next Steps and Challenges

- Prove ILE integrated OLEDs on larger panels
  - Processibility
  - Compatibility with other layers
- Uniform ILE surface and low surface roughness
- Low Moisture permeability

Room for more improvements

- Optimum scatterer size
- Optimum binder RI
- Optimum scatterer RI

Commercialize
Conclusion

• High Refractive Index is needed to improve light extraction efficiency

• PixClear High Refractive Index structures can improve efficiency in OLED lighting devices achieving as high as 90 lm/W efficacy

• The formulation is solution processable and can be used for both rigid as well as flexible substrates
Acknowledgements

- DOE SBIR Phase I, Phase II and phase IIB Award #DE-SC0011295
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- DOE SBIR Phase I Award #DE-SC0017038, DE-SC0018604
- OLEDWorks LLC
- FROST & SULLIVAN Manufacturing Award
Thank you

For more technical details, read our white paper:
http://www.pixelligent.com/resources/

Dr. Selina Monickam (Product Development Manager)
sthomas@pixelligent.com