High Refractive Index Nanocomposites For Light Extraction
In Solid State Lighting
Lighting Japan 2015

www.pixelligent.com
Outline

- Pixelligent Technologies: Company & Technology Overview

- High Refractive Index (R.I.) ZrO2 Enabled Nanocomposites As Internal Light Extraction materials (ILE) for OLED Lighting

- High R.I. ZrO2 Enabled Nanocomposites As Encapsulation For LED Lighting

- Conclusions
Company Overview

Corporate Highlights

- Advanced Materials Company leveraging next-generation nanotechnology
- One Technology, Many Markets
  - All products utilize the same technology, processes, and manufacturing platform
- 5 MT Capacity today, 40 MT 2H, 2015
- Global Customer Base and Presence

Focus End Markets

Solid State Lighting

- LED Chip Encapsulation
- OLED Lighting

Optical Components & Films

- Displays
- Optical Components
Global Capabilities

- **Baltimore, MD**
  - Headquarters
  - Sales & Distribution
  - Applications Support
  - Manufacturing

- **Baton Rouge, LA**
  - Sales & Distribution
  - Applications Support

- **St. Louis, MO**
  - Sales & Distribution
  - Applications Support

- **Seoul, Korea**
  - Sales & Distribution
  - Applications Support

- **Tokyo, Japan**
  - Sales & Distribution
  - Applications Support
- ZrO2 Nanocrystal Dispersions & Nanocomposites

- Best Dispersions Available
  - Accurate Shape & Size Control (Std. size 5 nm)
  - High Loadings (>80wt%)
  - High Transparency >95%

- Solution Processable Nanocomposites
  - Dispersible in most commonly used solvents & polymers
  - Easy integration into existing manufacturing processes
Film thicknesses ranging from 50 nm to >500 microns can be achieved.
Manufacturing Process Overview:

40 MT Capacity 2H 2015

Nanocrystal Synthesis: Control Size & Shape
Capping Process: Surface Engineering
Centrifugal Wash & Final Dispersion
Final Product: Clear Dispersion

5 nm ZrO₂ nanocrystals produced
Application selection stage
Dispersion into target solvent, monomer, or oil
Crystal Clear Dispersion even at loading >80% wt.

Highly scalable for mass production
ZrO2 Synthesis

- Tightly controlled size & shape

Surface Engineering (Capping)

- Compatibility with various materials
- High loadings of ZrO2 in nanocomposites

Mfg. Scale

- Stable, clear dispersions & nanocomposites
- High volume manufacturing

Benefits In Solid State Lighting

- Best combination of properties:
  - Achieve high R.I. (> 1.80)
  - Maintain high % T (> 90%)
  - Maintain low haze (<1%)
- Drop in technology for OLEDs & LEDs
  - Acrylics, Siloxanes, Silicones
  - Solution processable & compatible with current mfg. processes
- Smooth, scatter free, highly transparent coatings
- Products with consistent quality at manufacturing scale

Patents and trade secrets cover all aspects of technology
OLED Lighting
Internal Light Extraction (ILE)

Pixelligent High R.I. Nanocomposites
OLED Lighting: Many Benefits and Novel Applications

Quality & Experience

- Diffused, Ultra-Slim, Flexible & Simple

Energy Efficiency

<table>
<thead>
<tr>
<th>Savings</th>
<th>LED</th>
<th>OLED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumens/Watt</td>
<td>~110 -120</td>
<td>~ 60 -75</td>
</tr>
</tbody>
</table>

Energy efficiency/Light extraction a critical challenge

Novel Applications
OLED Lighting Challenge: Low Light Extraction Efficiency

- Lower lifetime
- Higher costs ($/lumen)

Source: IDTEChX OLED Lighting Market Report
OLED Lighting: Challenges of Light Loss

Only 20 % - 30% Light Is Coupled Out of OLED Lighting Device
# Approaches To Enhance Light Extraction In OLED Lighting

<table>
<thead>
<tr>
<th>Technology</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>External Out-Coupling</strong></td>
<td>Simpler technology to integrate</td>
<td>Only ~20 % of light available for extraction</td>
</tr>
<tr>
<td>High R.I. Glass</td>
<td>Easy solution</td>
<td>Very expensive</td>
</tr>
<tr>
<td>Brightness Enhancement Film</td>
<td>Established</td>
<td>Expensive</td>
</tr>
<tr>
<td><strong>Internal Out-Coupling</strong></td>
<td>Highest impact on extraction efficiency</td>
<td>More complicated to integrate</td>
</tr>
<tr>
<td>Nano-imprinted scattering layer</td>
<td>High impact on extraction efficiency</td>
<td>Nano-imprint technology not scalable at this time</td>
</tr>
<tr>
<td>High R.I. scattering layer</td>
<td>Highest impact on extraction efficiency</td>
<td>Does not provide smooth surface for ITO deposition on scattering layer and results in loss of yield</td>
</tr>
</tbody>
</table>

**Pixelligent Solution**

High R.I. Planarizing & Smooth ZrO2 Nanocomposites For ILE
Enhanced Light Extraction with Internal Light Outcoupling

Pixelligent High R.I. ZrO2 Nanocomposites As Smoothing ILE Layer

- Provide high R.I. (>1.8) and high transmittance (>95%)
- Provide highly planarized and smooth surface over scattering structures
- Enable high yield ITO deposition on smooth surface
Pixelligent High R.I. ZrO2 Nanocomposites As OLED ILE

**Refractive Index of Pixelligent ILE Films**

- High R.I. of 1.70 ~ 1.85 Demonstrated
Pixelligent High R.I. ZrO2 Nanocomposites As OLED ILE

% Transmittance of Pixelligent ILE Films

- >95% Transmittance Demonstrated
Pixelligent High R.I. ZrO2 Nanocomposites As OLED ILE

Pixelligent ILE-2 Thermal Stability of R.I.

Pixelligent ILE-2 Thermal Stability of % T

- R.I. and % Transmittance are stable at 200 C Conditions
- Higher temperature stability studies in progress
Surface Smoothness Properties of Pix ILE-2

Pix ILE – 2
Before thermal treatment

Ra: 0.41 nm
RMS: 0.52 nm

Pix ILE – 2
After 250 C/5 min

Ra: 0.40 nm
RMS: 0.50 nm

Smooth surface enables high yield ITO coating process and lowers device failures
Enhanced Light Extraction With Pixelligent High R.I. ZrO2 Nanocomposites

Pixelligent ZrO2 Enabled ILE In OLED Device

Relative Light Extraction Efficiency

Lumens/Watt

> 200% Improvement in Light Extraction Improvement in Device with ZrO2 ILE
Summary: Pixelligent High R.I. ZrO2 Nanocomposites For OLED ILE

<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</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>In progress, initial results promising</td>
</tr>
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Samples Available For Testing
Pixelligent’s High R.I. ILE Product Roadmap

**Proof of Concept Samples/Test Capability/Data**

**Commercial Product**

<table>
<thead>
<tr>
<th>2014</th>
<th>2015</th>
<th>2016</th>
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<tbody>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
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<tr>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
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**Single Layer ILE:**

- **High R.I. Solvent Dispersions**
  - 2014: Proof of Concept Samples/Test Capability/Data
  - 2015: Commercial Product
  - 2016: Commercial Product

- **High RI ILE Smoothing Layer (Formulated)**
  - 2014: Proof of Concept Samples/Test Capability/Data
  - 2015: Commercial Product
  - 2016: Commercial Product

- **Integrated ILE Smoothing + Scattering**
  - 2014: Proof of Concept Samples/Test Capability/Data
  - 2015: Commercial Product
  - 2016: Commercial Product

**Graded Index ILE:**

- **Integrated process for GRIN layers embedded with Scatterers**
  - 2014: Proof of Concept Samples/Test Capability/Data
  - 2015: Commercial Product
  - 2016: Commercial Product

- **Integrated Process for Producing 3D GRIN layers embedded with scatterers**
  - 2014: Proof of Concept Samples/Test Capability/Data
  - 2015: Commercial Product
  - 2016: Commercial Product

- **ΔRI ~0.25; chemical compatible, 200C stable 30 min, <3 nm RMS**

(RI>1.8@633, stable up to 250C for 30 min, <1 nm RMS)

(RI>1.75@633, chemical compatible, 200C stable 30 min, <1 nm RMS)
LED Lighting
Light Extraction with High R.I.
Nanocomposites
LED Lumen Losses Due To Refractive Index Mismatch

Challenge:

• Refractive index (R.I.) mismatch between chip (High R.I.), phosphor (High R.I.), and encapsulation materials (Low R.I.) causes total internal reflection at multiple interfaces

• Results in lumen loss and high operating temperature leading to shorter device lifetimes

Solution:

• Increase the R.I. of encapsulating materials (usually silicones) to reduce the mismatch and increase the lumen output
Potential to increase lumen output by 5% - 10% with high R.I. ZrO2-Silicone Nanocomposites
Challenges To Achieve High R.I. ZrO2-Silicone Nanocomposites For LED:

- Silicones are highly viscous materials:
  - Difficult to disperse ZrO2 nanocrystals

- High temperature LED operating conditions:
  - Difficult to achieve stable optical properties
  - Stable lumen gain
  - Mechanical properties

Pixelligent Approach High R.I. ZrO2-Silicone Nanocomposites For LED:

- Surface engineering of ZrO2 to achieve compatibility with silicones
  - Clear, transparent, thermally stable nano-composite films

- Formulation optimization to achieve desired mechanical properties
  - Stable optical properties, stable lumen gain, desired mechanical properties

- Currently engaged with the leading LED package manufacturers and material suppliers
Pixelligent ZrO₂ – Silicone Nanocomposite Films
With Commercial Di-Methyl Silicone

- R. I. increase from 1.43 to 1.55 at 450nm at 70% wt. loading
- Films stable after 250°C/1min solder reflow process
- Stable in 1 week thermal aging at 200°C
Pixelligent ZrO₂ – Silicone Nanocomposite Films
With Commercial Methyl-Phenyl Silicone

- R. I. increase from 1.54 to 1.62 at 450nm at 70% wt. loading
- Films stable after 250C/1min solder reflow process
- Stable in 1 week thermal aging at 200 C
Pure Methyl Phenyl Silicone vs. Pixelligent ZrO₂ containing Di-Methyl Silicone

- Achieves R.I. of 1.55 equivalent to that of Methyl-Phenyl Silicones
- Maintains the benefits of optical stability of Dimethyl Silicone
Pixelligent ZrO₂ does not shift the emission spectrum relative to control
In some cases required ~ 20% less phosphor to match emission properties of control
## Product Roadmap for LED Silicone Applications

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- **2014**
  - With Commercial Methyl Phenyl Silicons
  - With Commercial Dimethyl Silicons
  - Further Development with customers

- **2015**
  - Solvent Free Systems For Spray Process

- **2016**
  - Solvent Free Systems For Dispense Process

- **2017**
  - Model Systems
  - Reliability and New Formulations

**POC Product/Test Capability/Data**

**Commercial Product**

**Solvent Free Formulations**

**Phosphor Deposition - Dispense**
**Conclusions:**

**Pixelligent Value Proposition: OLED Lighting**

**High R.I. Nanocomposite ILE:**
- High R.I. (>1.75 - 1.85)
- High transmittance (> 90%)
- High planarization and smoothness

**OLED Lighting Manufacturers:**
- > 200% Improvement in light extraction
- Significantly improve yields
- Reduce costs
- Increase lumens/$

**Pixelligent Value Proposition: LED Lighting**

**High R.I. Silicone Nanocomposites:**
- High R.I. (up to 1.70)
- High transmittance (>90%)
- Good thermal stability (200 C)

**LED Package Manufacturers:**
- Increase lumen output 2% - 10%
- Materials usage optimization
- Reduced costs
- Increase lumens/$
Thank You!!

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