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The Clear Solution™

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.) ZrO_2 Enabled Nanocomposites As Internal Light Extraction materials (ILE) for OLED Lighting
- High R.I. ZrO_2 Enabled Nanocomposites As Encapsulation For LED Lighting
- Conclusions

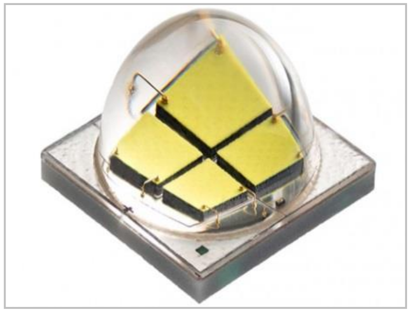
Company Overview

Corporate Highlights

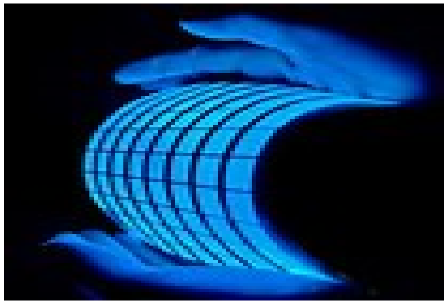
- Advanced Materials Company leveraging next-generation nanotechnology
- One Technology, Many Markets
  - All products utilize the same technology, processes, and manufacturing platform
- 5 MT Capacity today, 40 MT 2H, 2015
- Global Customer Base and Presence

Focus End Markets

Solid State Lighting



LED Chip Encapsulation



OLED Lighting

Optical Components & Films

Displays

Optical Components

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Global Capabilities

Baltimore, MD
Headquarters
Sales & Distribution
Applications Support
Manufacturing

Baton Rouge, LA
Manufacturing

St. Louis, MO
Sales & Distribution

Seoul, Korea
Sales & Distribution
Applications Support

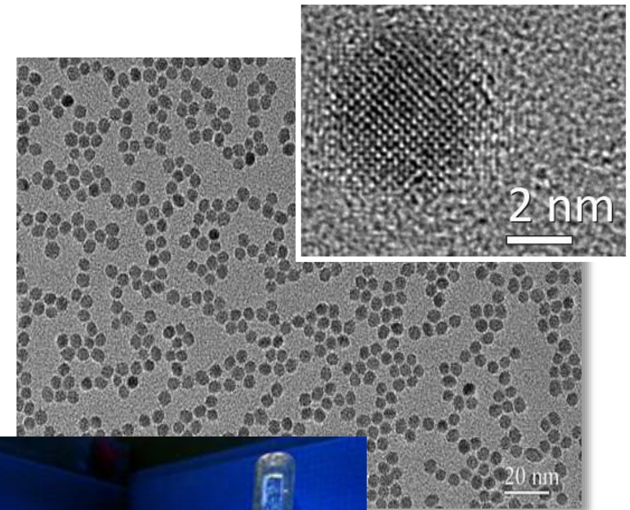
Tokyo, Japan
Sales & Distribution
Applications Support

Pixelligent's High R.I. Nano-Dispersions & Nanocomposites Technology

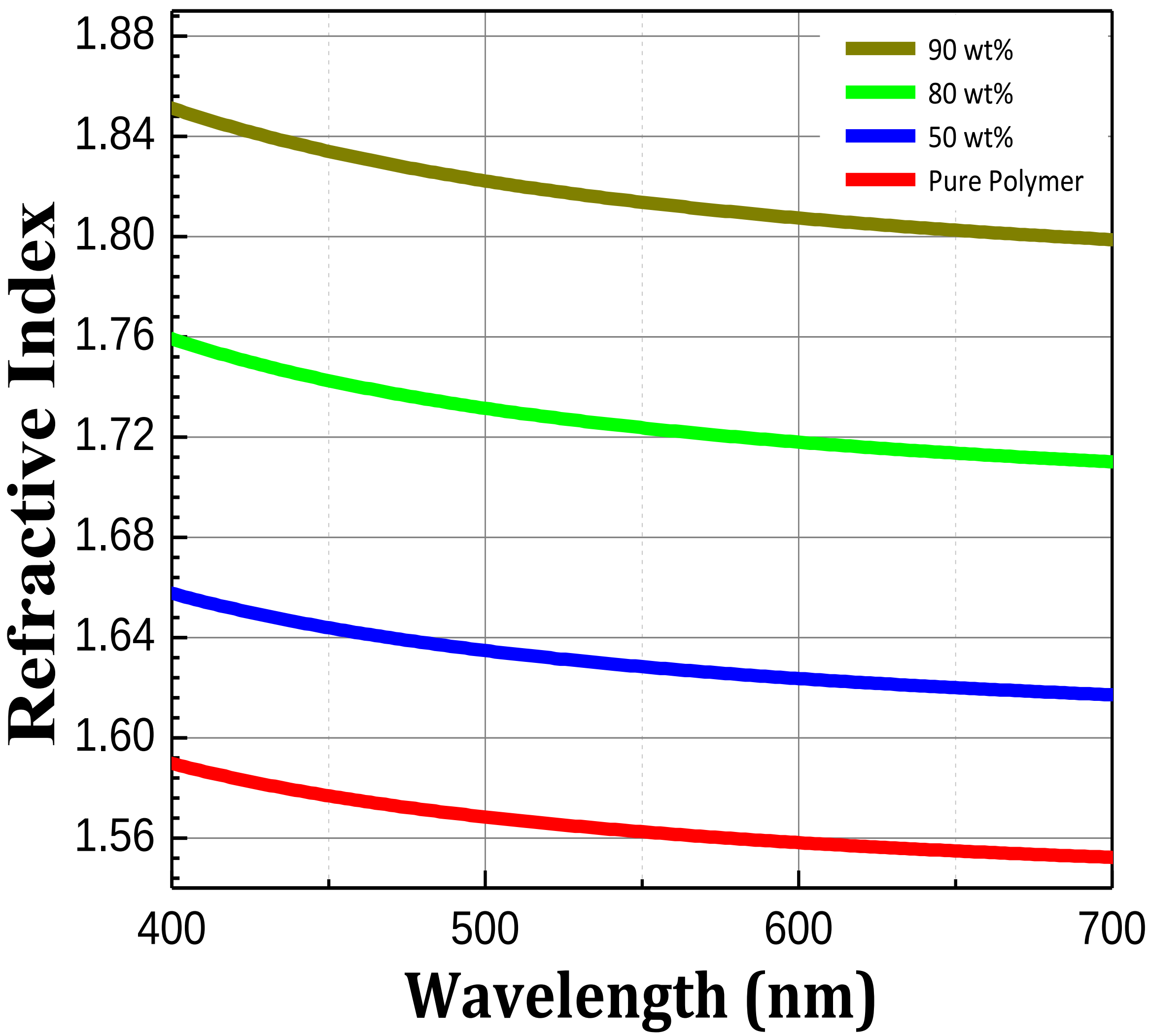
- ZrO2 Nanocrystal Dispersions & Nanocomposites

- 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



R.I. of ZrO_2 Nanocomposite 3 Micron Film in Acrylic Polymer



Loading	k (%T)	Haze
90 wt%	$<10^{-3}$	0.5%
80 wt%	$<10^{-3}$	0.5%
50 wt%	$<10^{-3}$	0.5%
0 wt%	$<10^{-3}$	0.4%

Film thicknesses ranging from 50 nm to >500 microns can be achieved

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Manufacturing Process Overview:

40 MT Capacity 2H 2015

Nanocrystal Synthesis: Control Size & Shape

5 nm ZrO_2 nanocrystals produced

Capping Process: Surface Engineering

Application selection stage

Centrifugal Wash & Final Dispersion

Dispersion into target solvent, monomer, or oil

Final Product: Clear Dispersion

Crystal Clear Dispersion even at loading >80% wt.

Highly scalable for mass production

Pixelligent Technology: Summary For Solid State Lighting

Technology	Features	Benefits In Solid State Lighting
ZrO2 Synthesis	▪ Tightly controlled size & shape	▪ Best combination of properties: ▪ Achieve high R.I. (> 1.80) ▪ Maintain high % T (> 90%) ▪ Maintain low haze (<1%)
Surface Engineering (Capping)	▪ Compatibility with various materials ▪ High loadings of ZrO2 in nanocomposites	▪ Drop in technology for OLEDs & LEDs ▪ Acrylics, Siloxanes, Silicones ▪ Solution processable & compatible with current mfg. processes
Mfg. Scale	▪ Stable, clear dispersions & nanocomposites ▪ High volume manufacturing	▪ 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

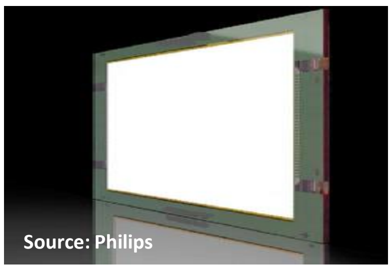
OLED Lighting: Many Benefits and Novel Applications

Quality & Experience

Energy Efficiency

Novel Applications

- Diffused, Ultra-Slim, Flexible & Simple


Source: Philips

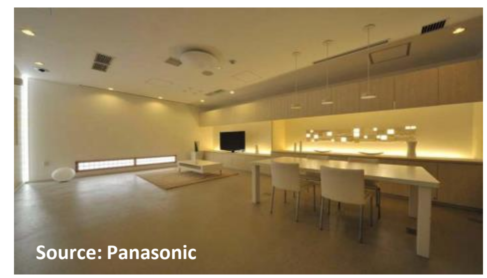
- Color Tunable


Source: OLED-Info

Savings	LED	OLED
Lumens/Watt	~110 -120	~ 60 -75

Energy efficiency/Light extraction a critical challenge


Source: Acuity Branding


Source: Panasonic


Source: Philips

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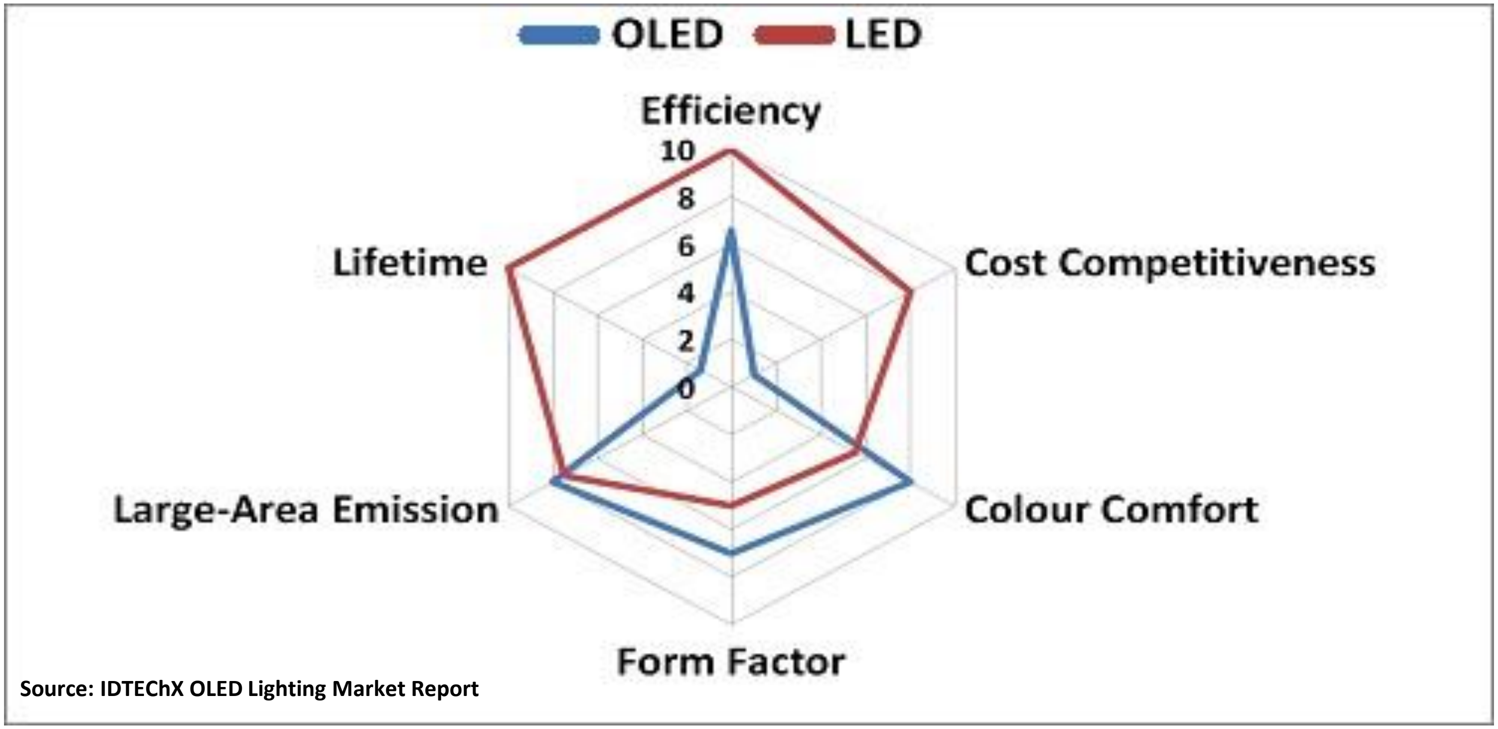
OLED Lighting: Key Challenge For Market Adoption



OLED Lighting Challenge: Low Light Extraction Efficiency

- **Lower lifetime**
- **Higher costs ($/lumen)**

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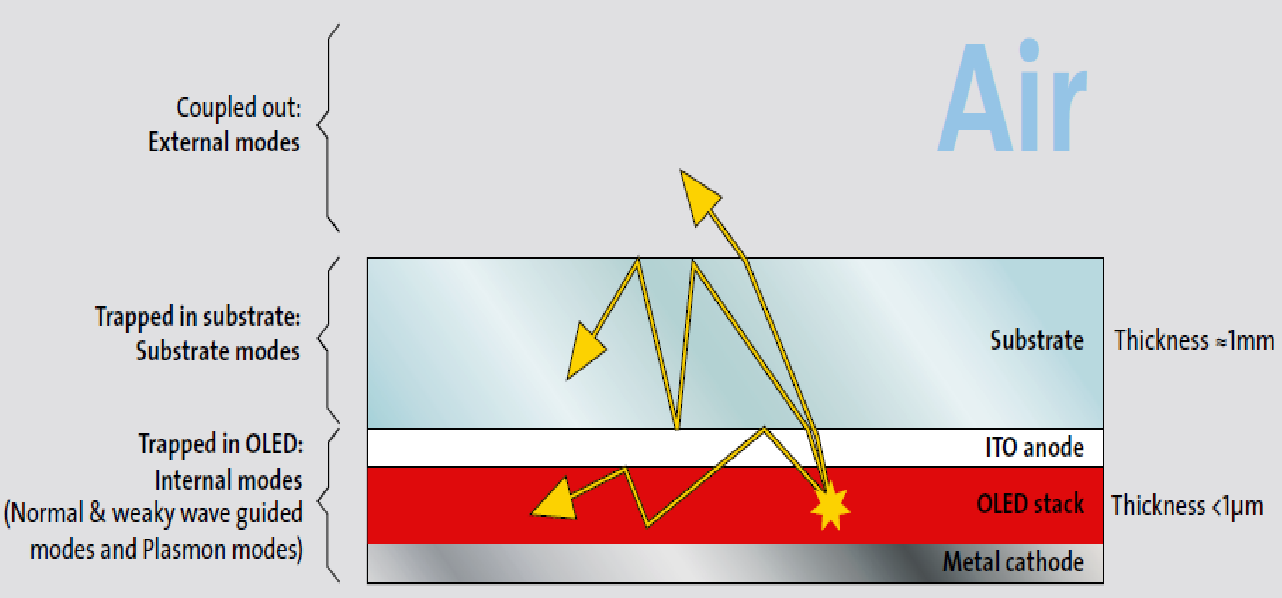
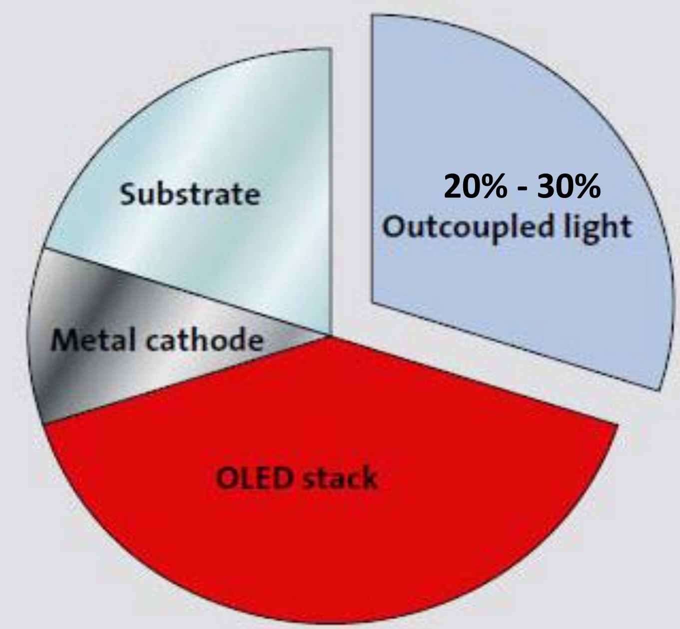
OLED Lighting: Challenges of Light Loss



Source: Novaled AG



Only 20 % - 30% Light Is Coupled Out of OLED Lighting Device

Approaches To Enhance Light Extraction In OLED Lighting

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

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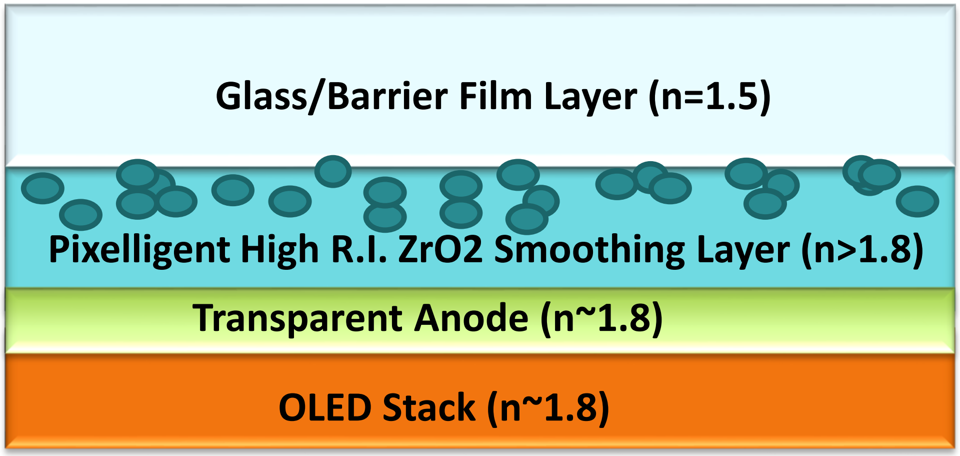
High R.I. Planarizing & Smooth ZrO2 Nanocomposites For ILE

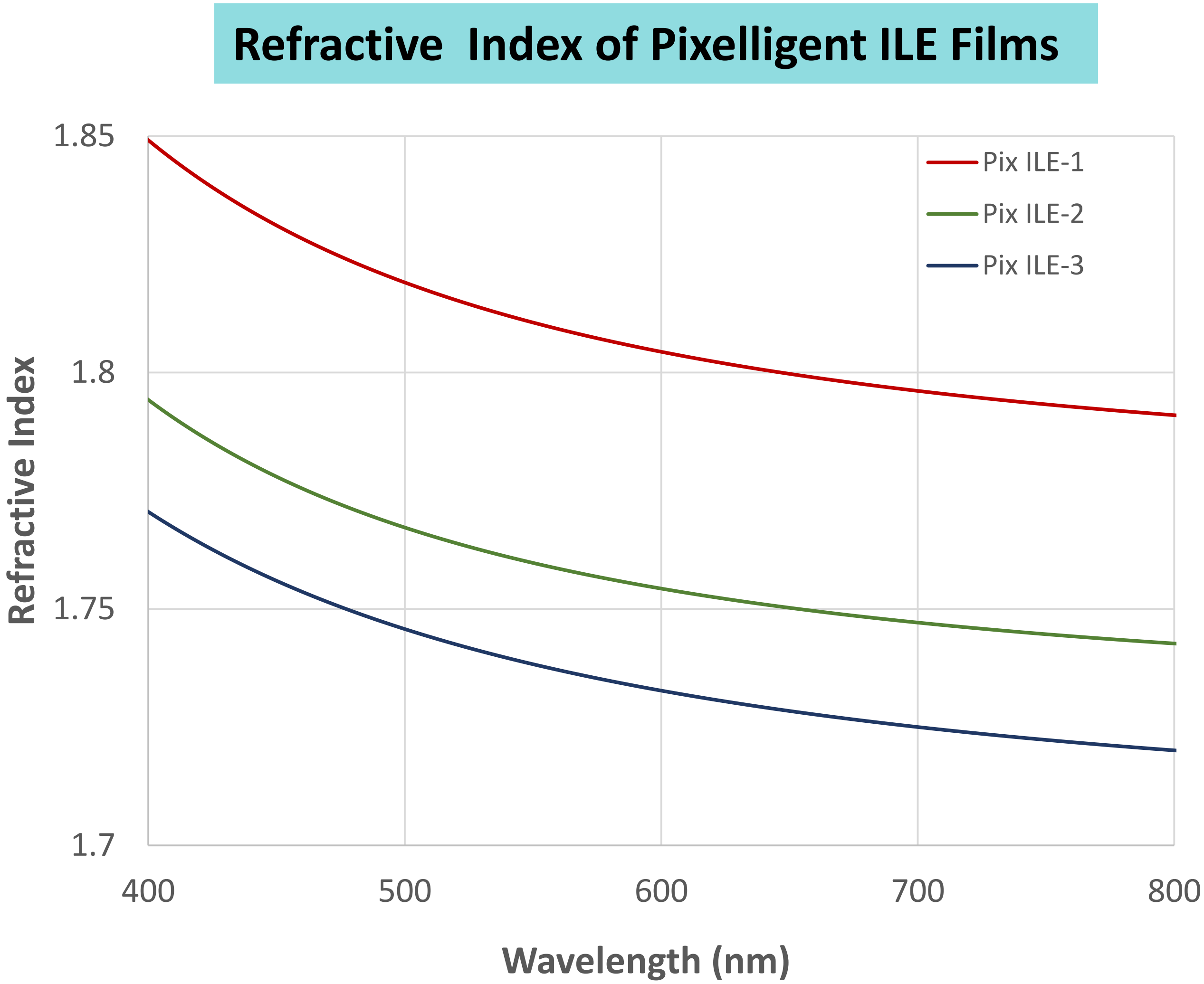
Enhanced Light Extraction with Internal Light Outcoupling

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



- **High R.I. of 1.70 ~ 1.85 Demonstrated**

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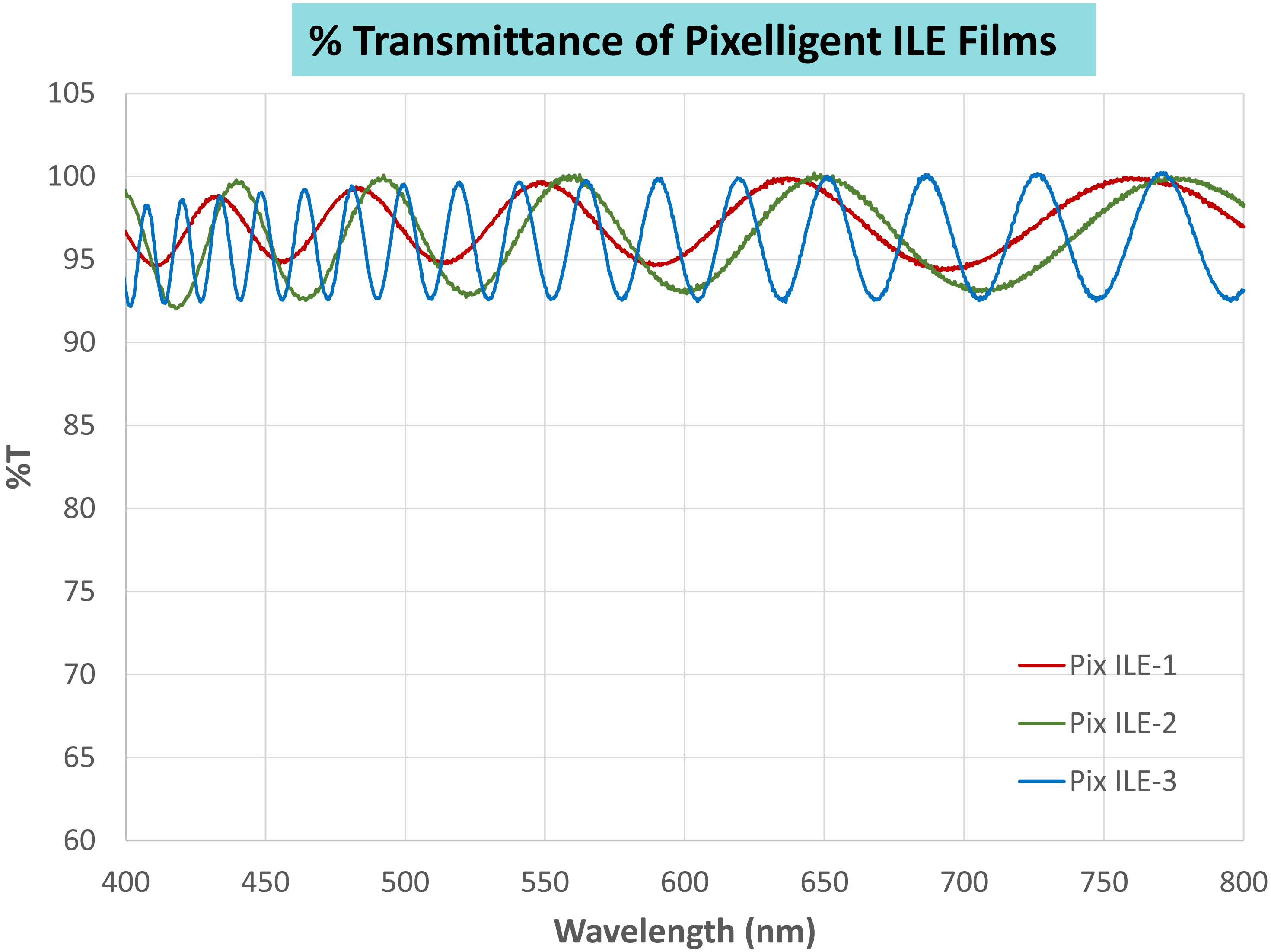
Pixelligent High R.I. ZrO2 Nanocomposites As OLED ILE



- >95 % Transmittance Demonstrated

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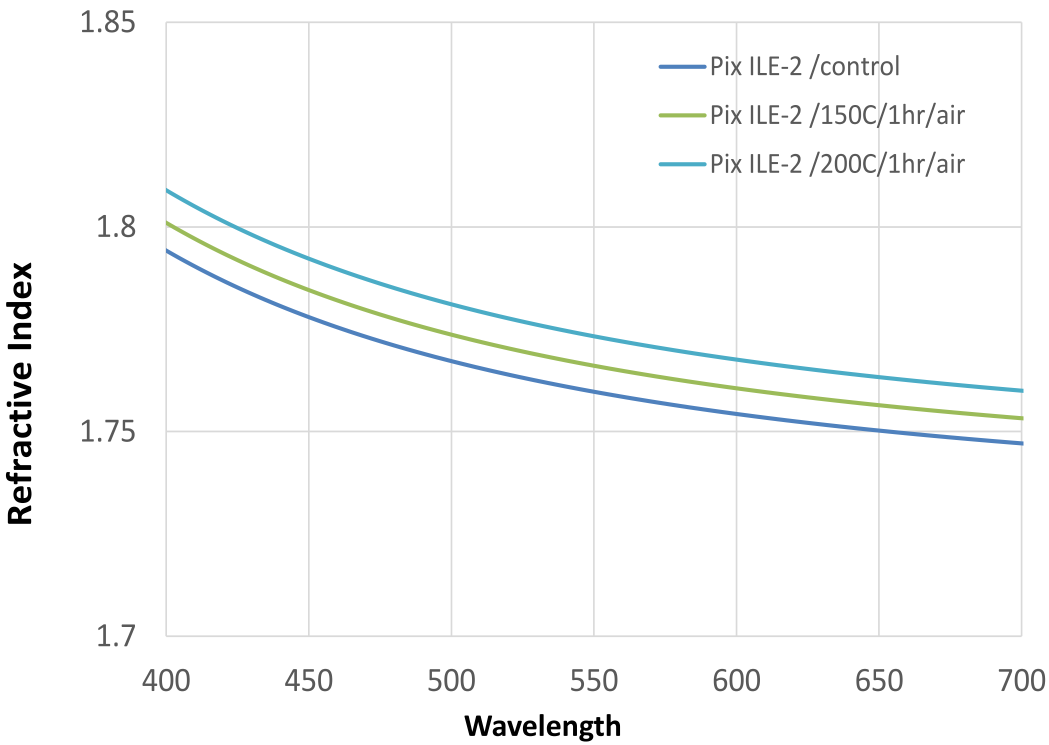
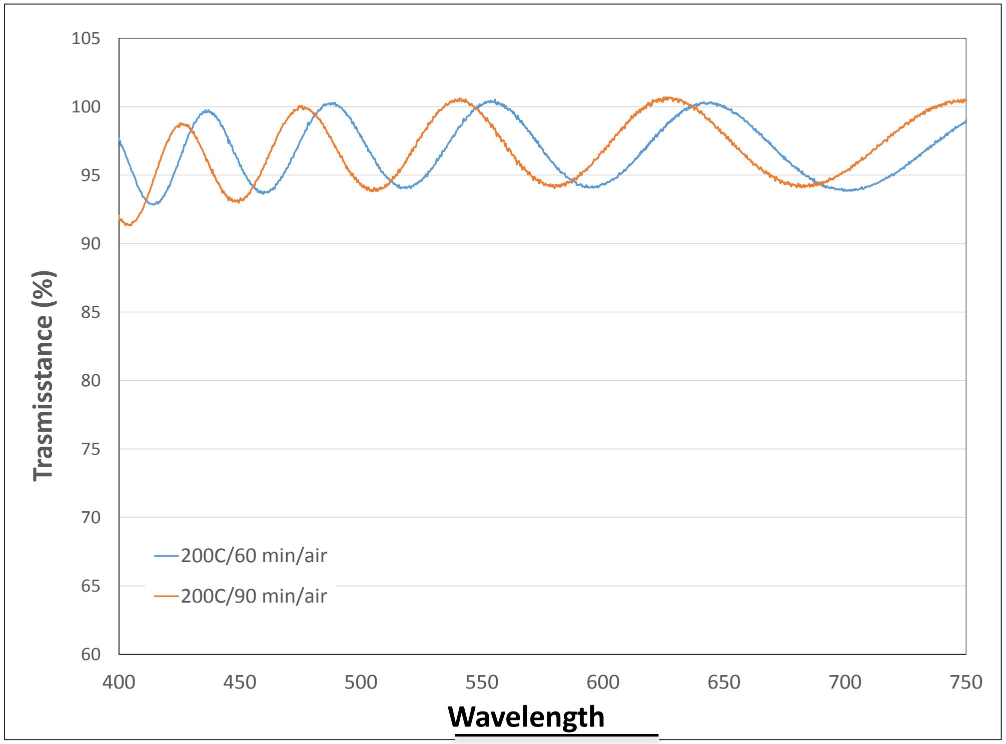
Pixelligent High R.I. ZrO2 Nanocomposites As OLED ILE

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

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Pixelligent High R.I. ZrO2 Nanocomposites As OLED ILE

Surface Smoothness Properties of Pix ILE-2

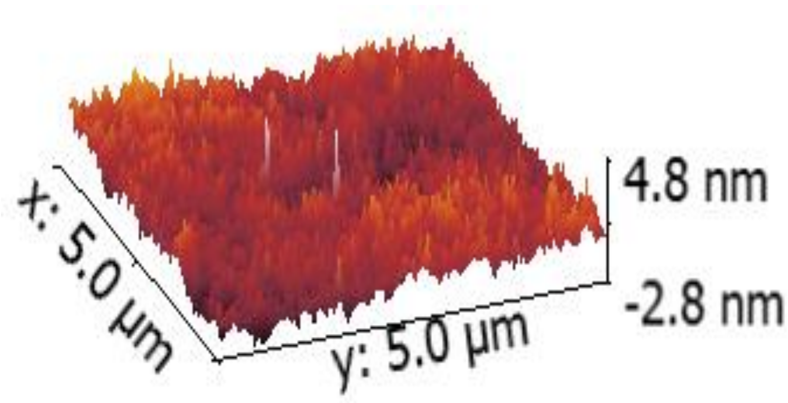
Pix ILE – 2
Before thermal treatment

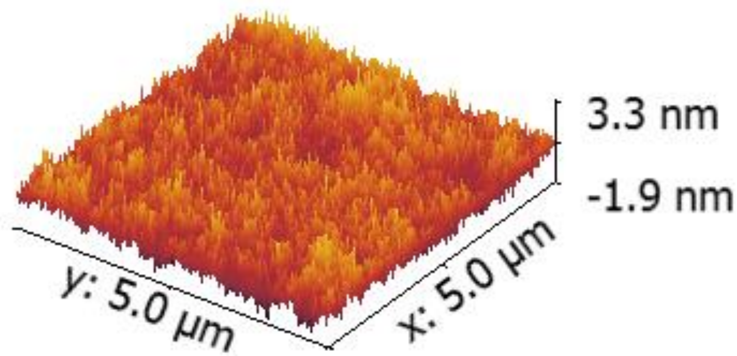
Ra: 0.41 nm
RMS: 0.52 nm

No Change

Pix ILE – 2
After 250 C/5 min

Ra: 0.40 nm
RMS: 0.50 nm

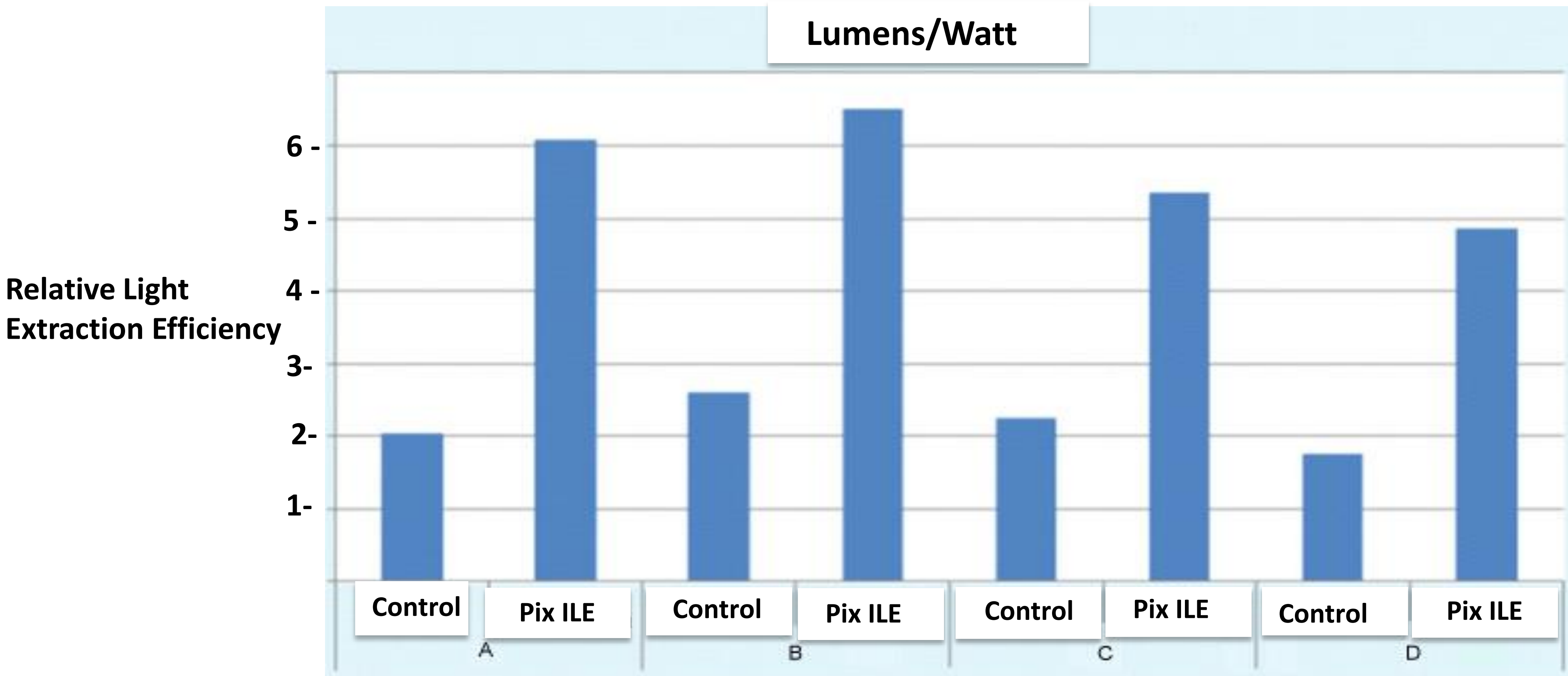




Smooth surface enables high yield ITO coating process and lowers device failures

Enhanced Light Extraction With Pixelligent High R.I. ZrO2 Nanocomposites

Pixelligent ZrO2 Enabled ILE In OLED Device



> 200% Improvement in Light Extraction Improvement in Device with ZrO2 ILE

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Summary: Pixelligent High R.I. ZrO_2 Nanocomposites For OLED ILE

Performance Criteria	Performance Targets	Pixelligent ILE
Optical Properties		
Refractive Index	> 1.75 – 1.85@ 550 nm	✓
% Transmittance	> 90% in visible region	✓
Physical Properties		
Smoothing Surface	Planarize scattering structures on substrate <1 nm Ra	✓
Compatible With Current Manufacturing Processes	Spin coating, slot die coating, screen printing, vaccum coating process, etc.	✓
Thermal Stability		
150 C – 250 C 30 min	Maintain High R.I. and High % T	✓
Chemical Properties		
Compatible with polymers	Maintain uniform, transparent planarizing coatings	✓
Compatible with scatterers	Maintain uniform, transparent planarizing coatings	✓
Compatible with chemical processing	Stable to ITO patterning processes, acids, bases, solvents, etc.	**In progress, initial results promising**

Samples Available For Testing

Pixelligent's High R.I. ILE Product Roadmap

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

☆ **Commercial Product**

2014				2015				2016			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4

Single Layer ILE:

High R.I. Solvent Dispersions — **(RI>1.8@633, stable up to 250C for 30 min, <1 nm RMS)**

High RI ILE Smoothing Layer (Formulated) — **(RI>1.8@633, stable up to 250C for 30 min, <1 nm RMS)**

Integrated ILE Smoothing + Scattering — **(RI>1.75@633, chemical compatible, 200C stable 30 min, <1 nm RMS)**

Graded Index ILE:

Integrated process for GRIN layers embedded with Scatterers

Integrated Process for Producing 3D GRIN layers embedded with scatterers

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

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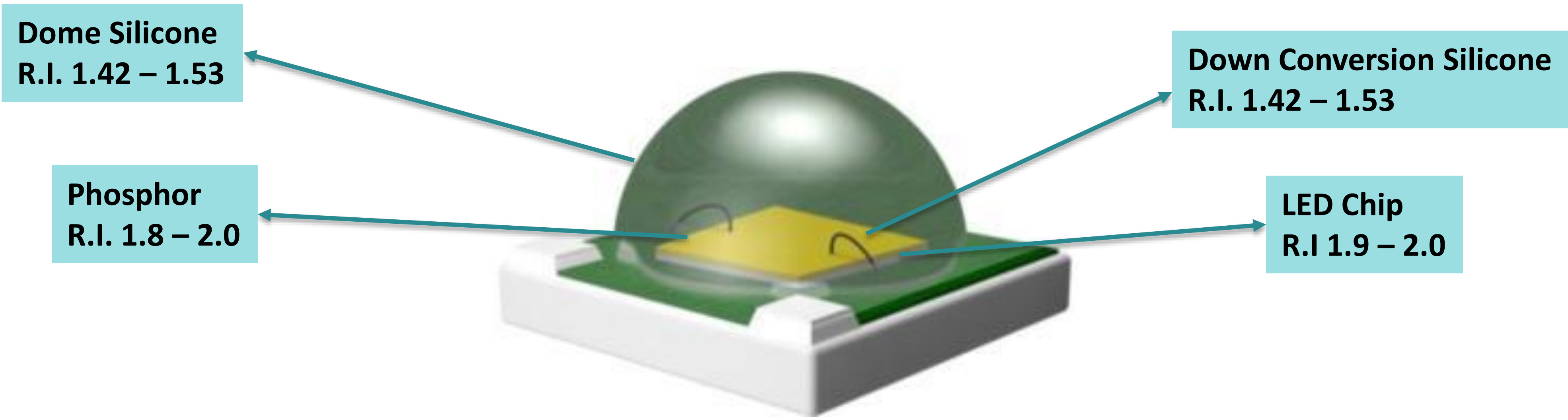
LED Lighting
Light Extraction with High R.I. Nanocomposites

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

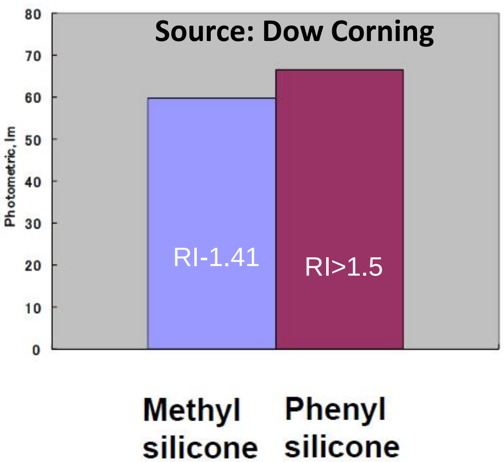
Solution:

- Increase the R.I. of encapsulating materials (usually silicones) to reduce the mismatch and increase the lumen output

Benefits of High R.I. Encapsulation Materials

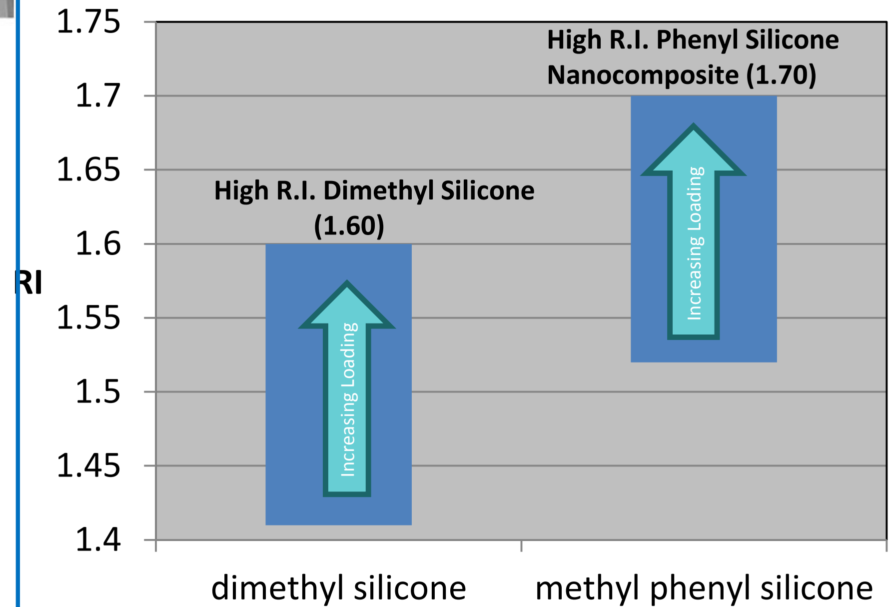
Refractive Index (R.I.) vs. Lumen Output

Lumen Output from Methyl and Phenyl Silicones



- Blue LED with silicone encapsulants containing yellow phosphor in 5052 packages
- A phenyl silicone provided ~11% higher lumen output as compared to a methyl silicone

Pixelligent Results: Demonstrated R. I. increase



Potential to increase lumen output by 5% - 10% with high R.I. ZrO_2-Silicone Nanocomposites

Pixelligent High R.I. ZrO_2 Enabled Silicone Nanocomposites For LED

Challenges To Achieve High R.I. ZrO_2-Silicone Nanocomposites For LED:

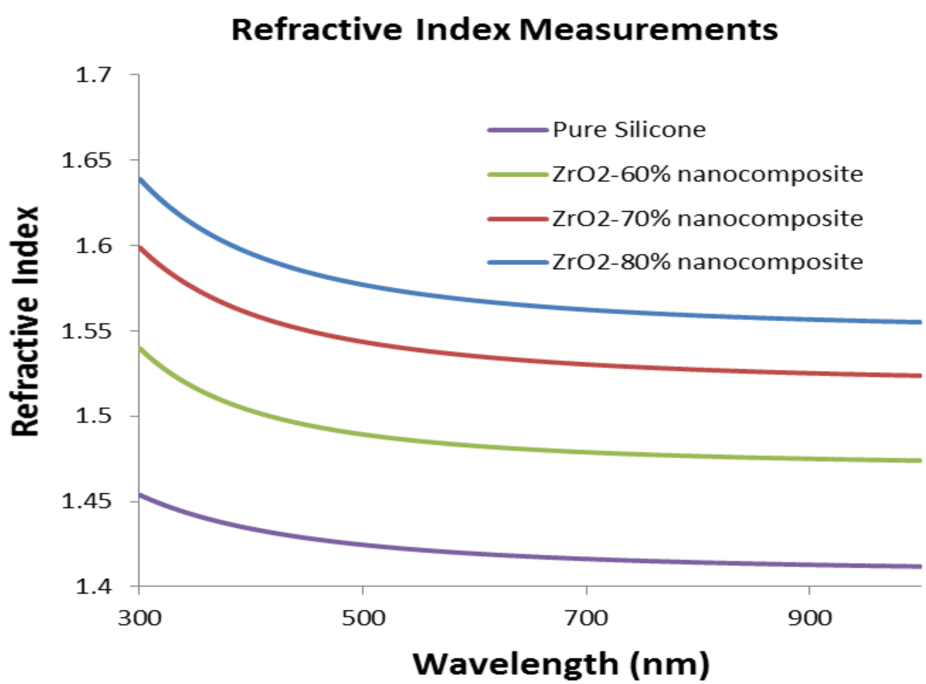
- Silicones are highly viscous materials:
  - Difficult to disperse ZrO_2 nanocrystals
- High temperature LED operating conditions:
  - Difficult to achieve stable optical properties
  - Stable lumen gain
  - Mechanical properties

Pixelligent Approach High R.I. ZrO_2-Silicone Nanocomposites For LED:

- Surface engineering of ZrO_2 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 High R.I. ZrO2-Silicone Nanocomposites For LED

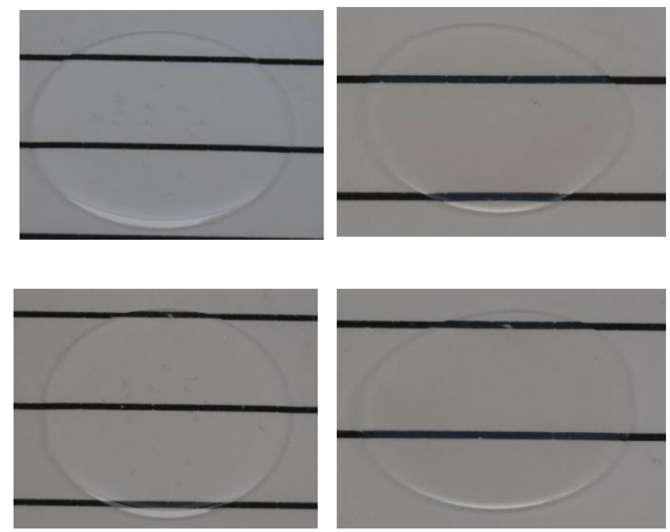
Pixelligent ZrO_2 – Silicone Nanocomposite Films With Commercial Di-Methyl Silicone



Pure silicone | 70% loading

Before solder reflow

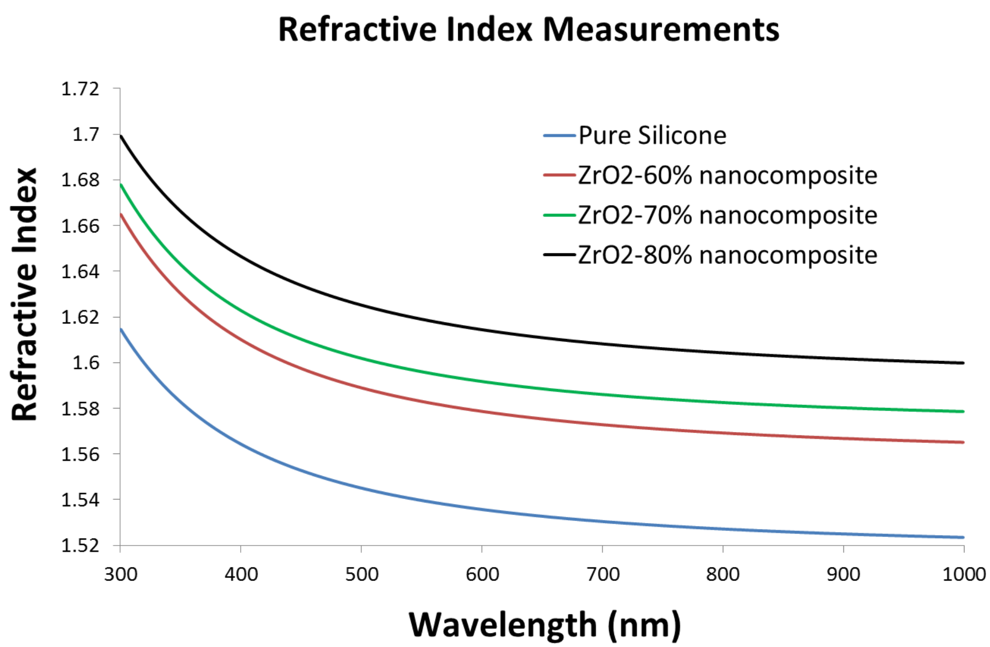
After solder reflow

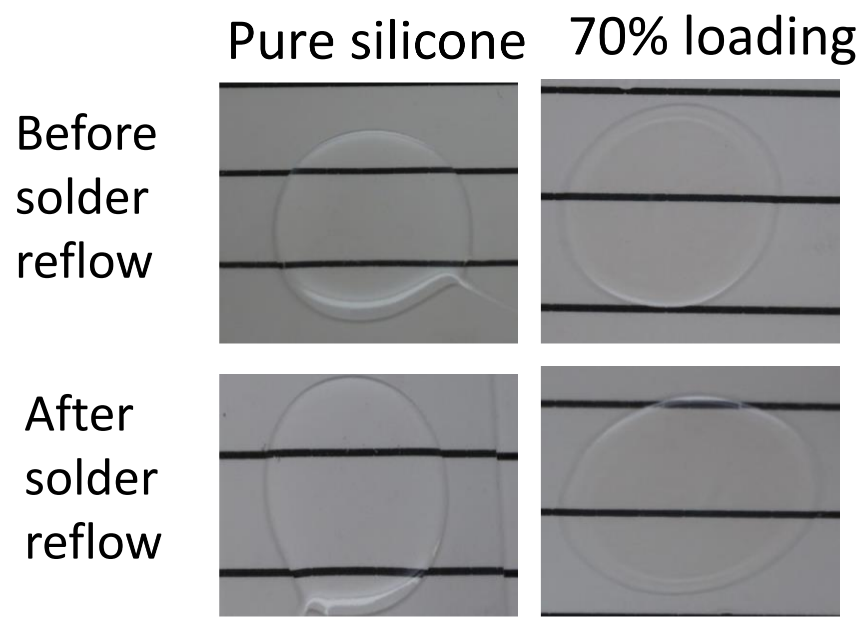


- R. I. increase from 1.43 to 1.55 at 450nm at 70% wt. loading
- Films stable after 250C/1min solder reflow process
- Stable in 1 week thermal aging at 200 C

Pixelligent High R.I. ZrO2 Enabled-Silicone Nanocomposites For LED

Pixelligent ZrO_2 – 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

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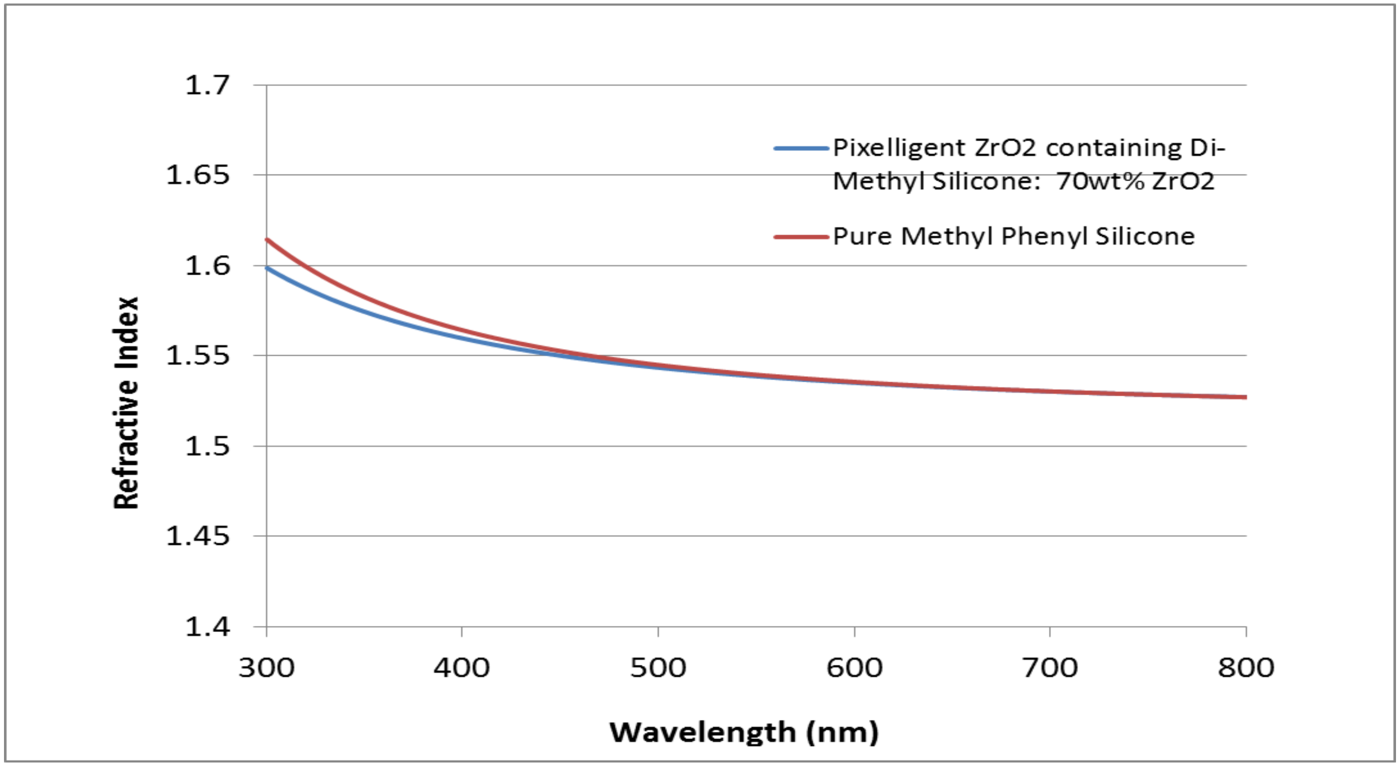
Pixelligent High R.I. ZrO2 Enabled-Silicone Nanocomposites For LED

Pure Methyl Phenyl Silicone vs. Pixelligent ZrO_2 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**

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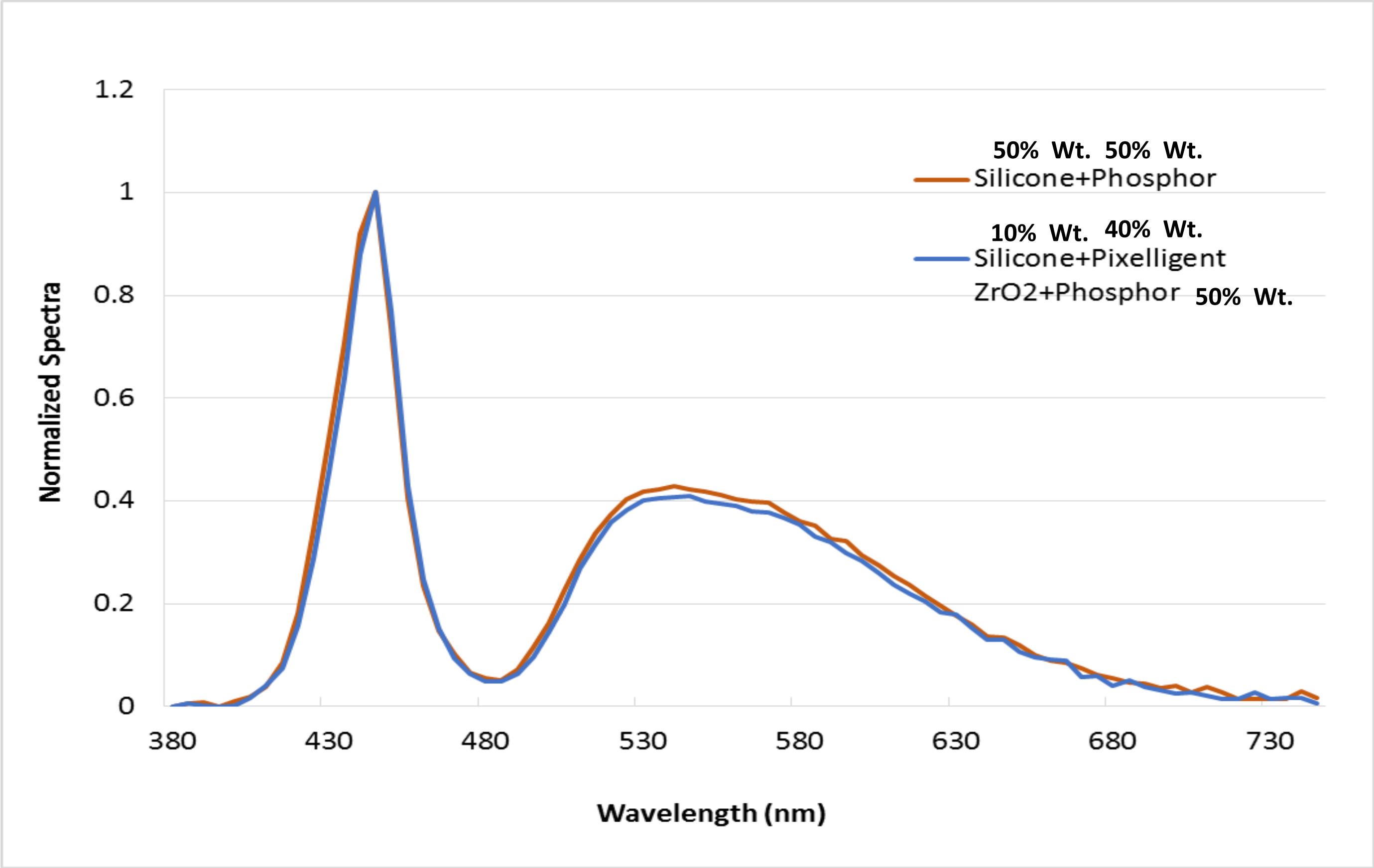
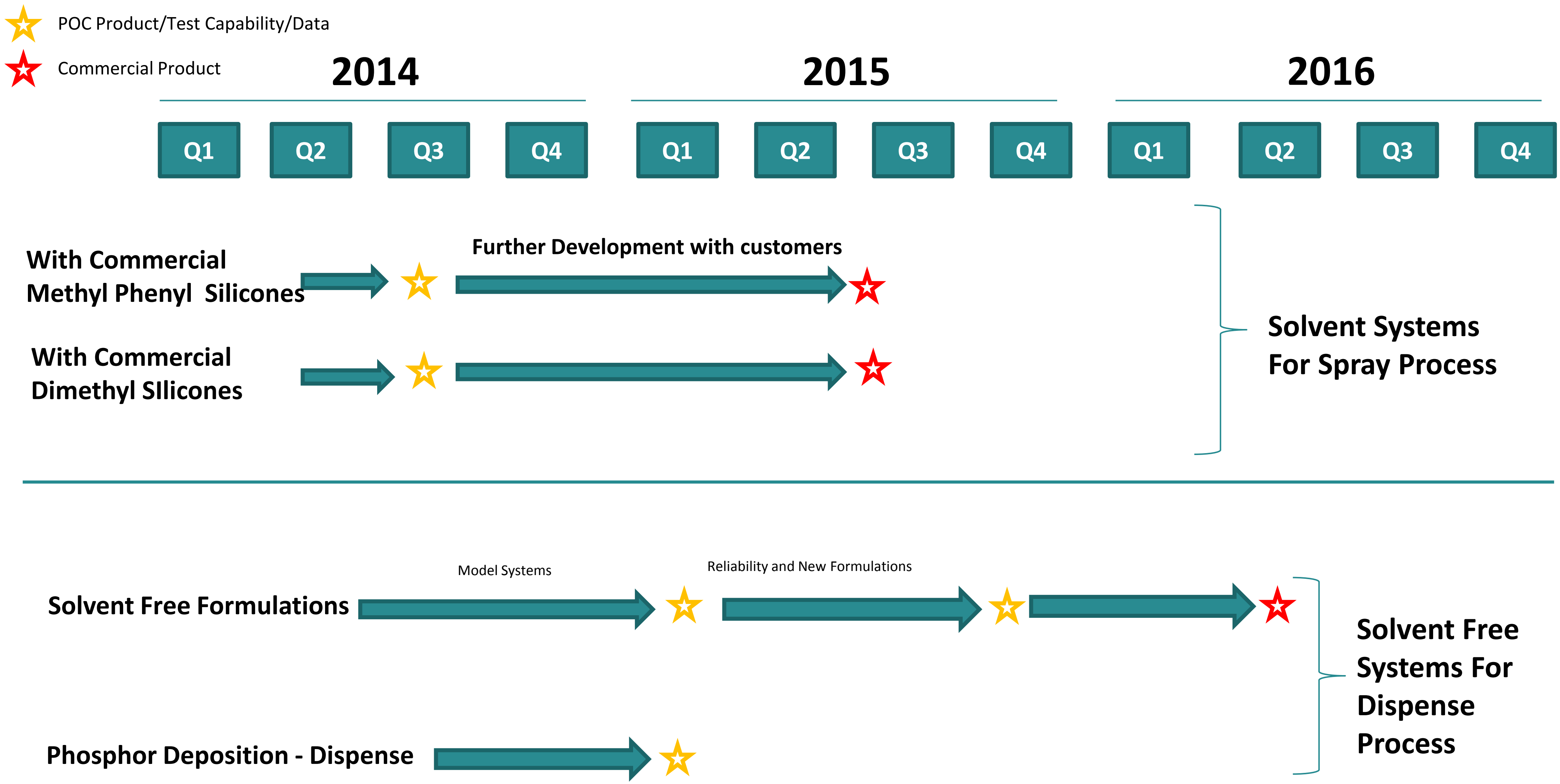
Emission Spectral Studies of ZrO2 Nanocomposites Films With Phosphor

Normalized Emission Spectra of Glass Domes Coated with Phosphor + Silicone + Pixelligent ZrO2 with White LEDs



- **Pixelligent ZrO_2 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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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!!

Shree Deshpande

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