The Clear Solution®

Use of High Refractive Index Materials in Display and Lighting Applications

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Outline

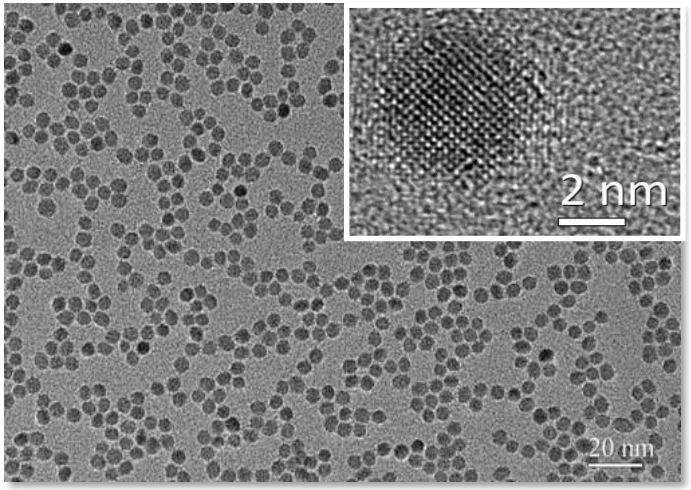
- Company Overview
- ZrO2 nanocrystals
- Dispersion properties
- Formulation Properties
- Nanocomposite Properties
- Applications of high refractive index materials in:
  - Displays
  - OLED lighting
  - LED lighting
- Material Requirements and Challenges
- Summary

Company Overview

Disruptive Technology	• Technology leader in Next Generation High-RI Nanocomposites
Key Markets Served	• OLED Display, HD Display, OLED Lighting, LED Lighting
Customers & Partners	• 50+ Leading Device, Advanced Materials, & Consumer Electronics Companies
Manufacturing	• 5 MT Pilot Baltimore, MD • 40 MT Full-scale, PA, 2H18
Locations	• Baltimore, MD - HQ • Iowa City, IA - Sales • Taipei, Taiwan - Sales
Distributors	• Korea, Japan, Taiwan

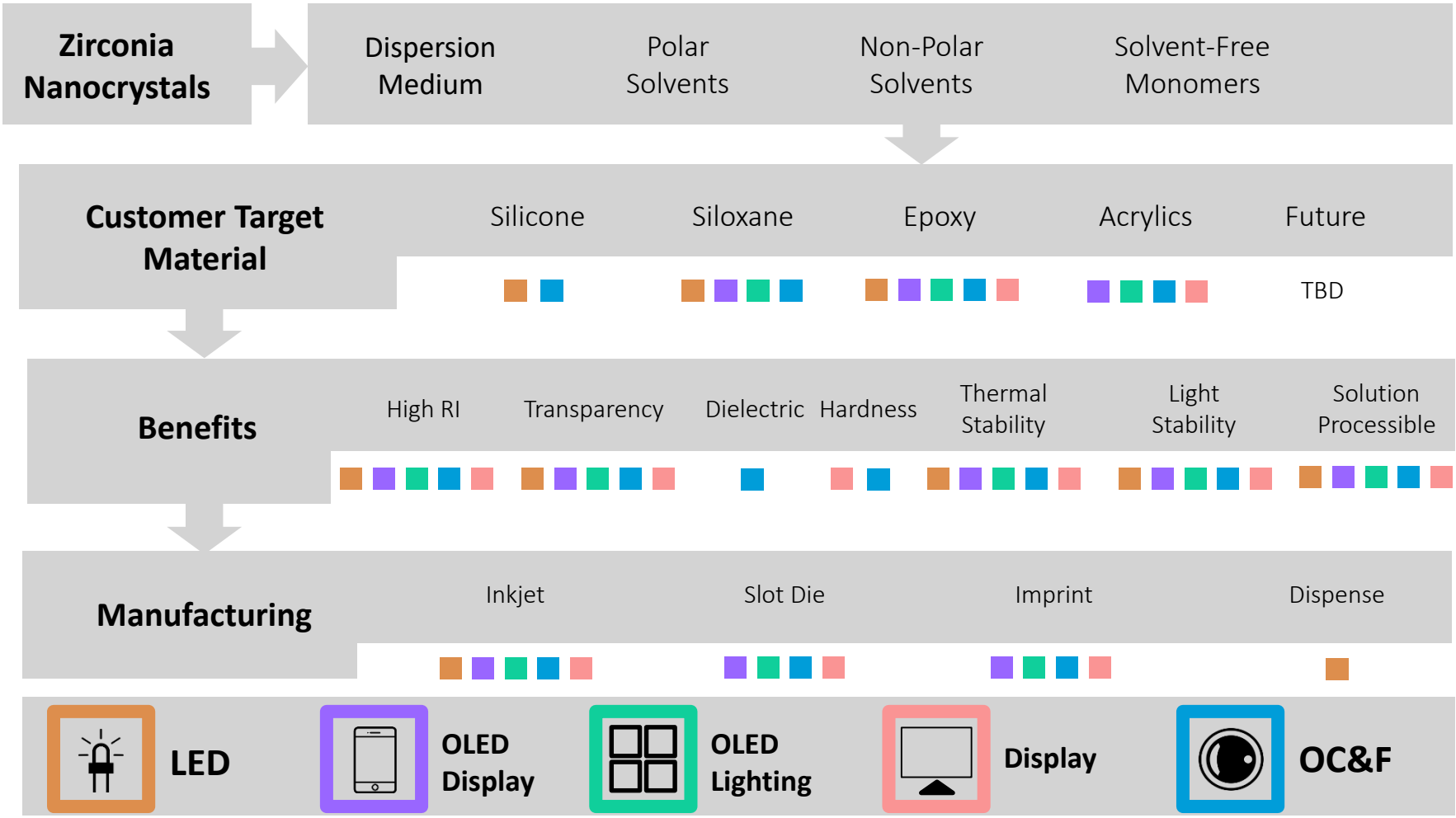
High Refractive Index Materials

- ZrO_2 Nanocrystals
  - High RI, transparent, not photoactive, hard
  - Uniform 5~10nm Spheres
- Highly Scaled Process
- Strong IP Position
  - 57 issued and pending patents



Nanocrystal Dispersion	**Formulation**	Deposition Method	Device with Nanocomposite
• Enables High RI (1.8), transparent (>95%), solution processable formulations	• Broad Compatibility with various monomers and polymers and curing methods • Low viscosity	• Compatible with commonly used deposition methods	• Improves brightness of displays • increases light output of OLED and LED lighting

Broad Compatibility



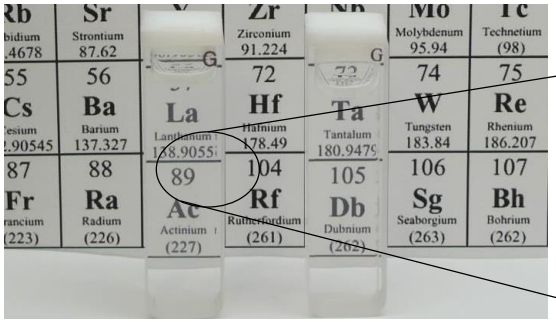
High Quality ZrO2 Dispersions

Nanocrystal Dispersion → **Formulation** → Deposition Method → Device with Nanocomposite

- Capped nanocrystals dispersed in solvent or monomer
- Many choices of capping agents depending on solvent/polymer
- No aggregation or settling

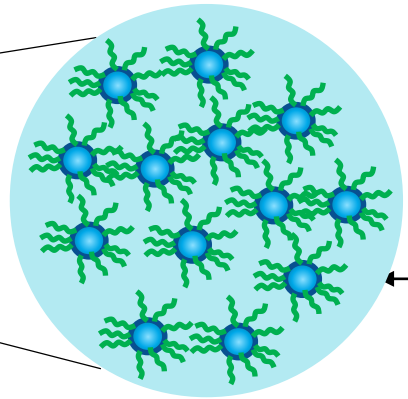
- Stable for years
- Low viscosity increase even at high loading of 75 wt%
- Transparent

Nanocrystal Dispersions



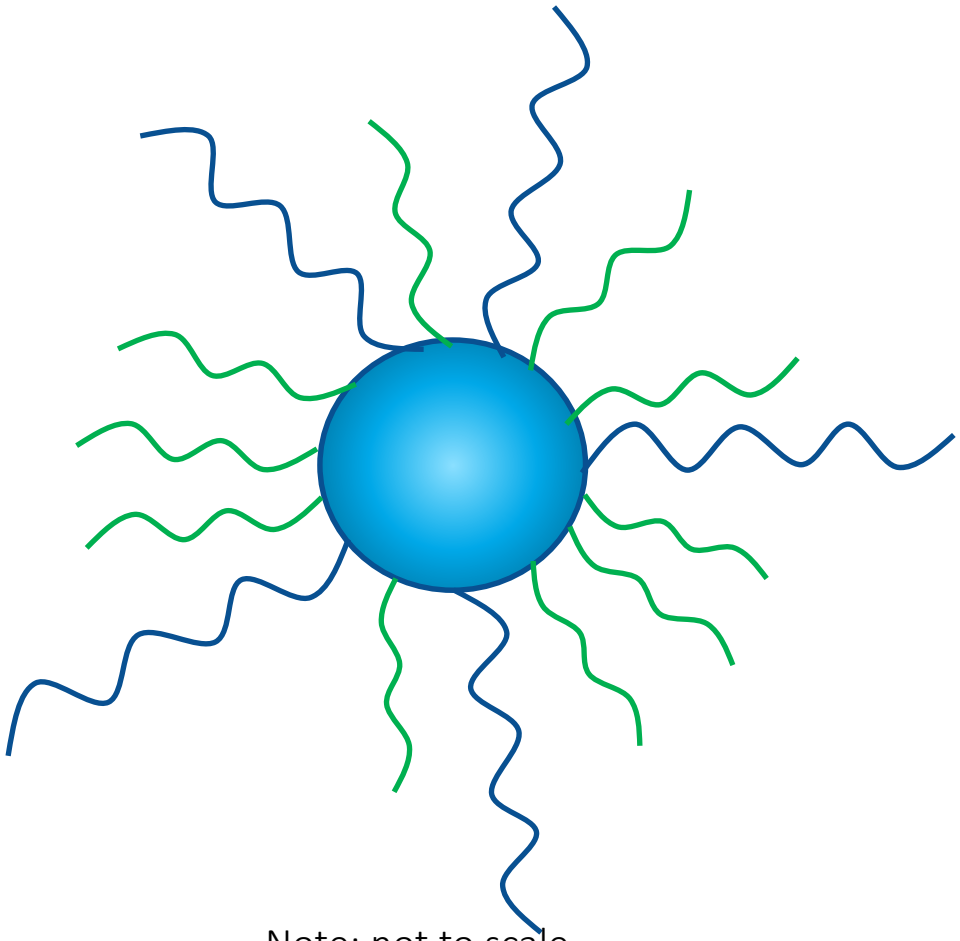
Left: 50wt% ZrO2 Nanocrystals | **Right:** Pure Xylenes

Capped Nanocrystals



Dispersion Media

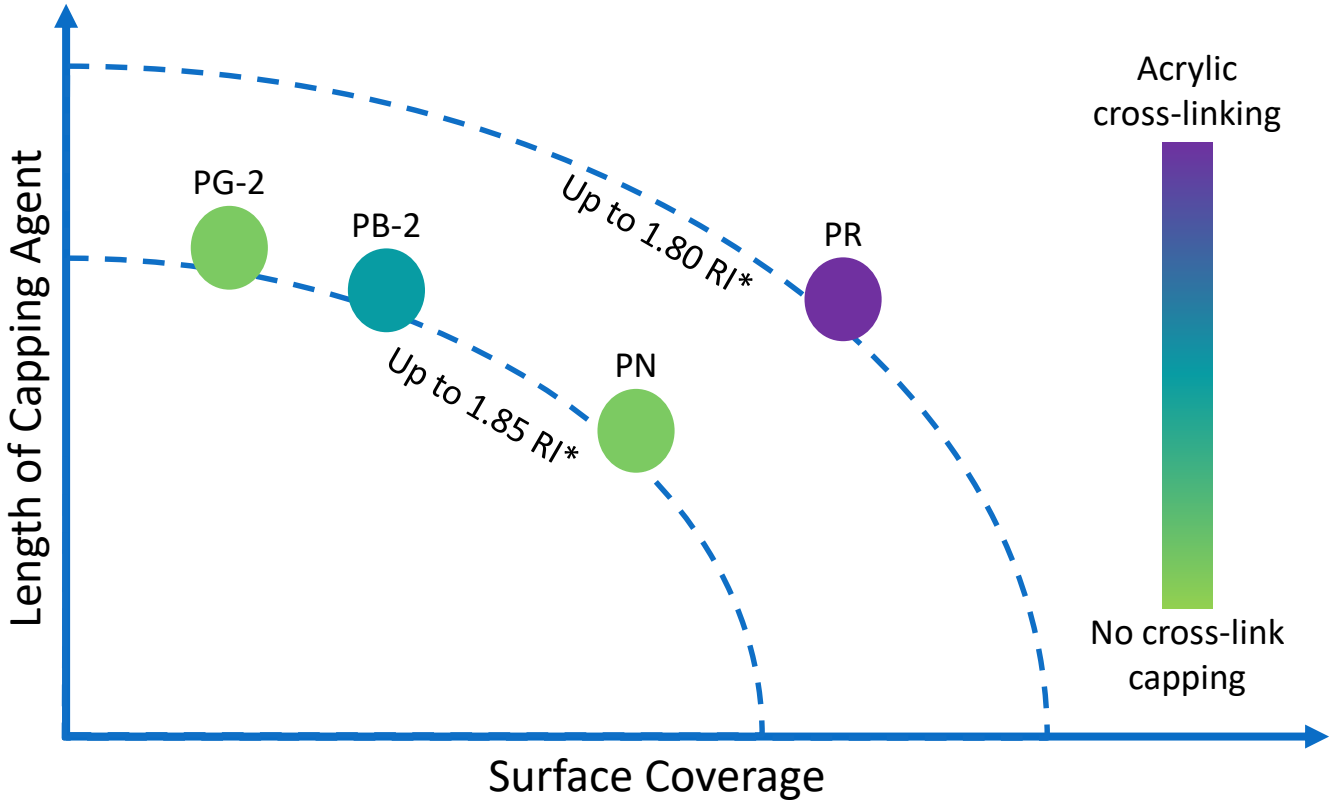
ZrO_2 Nanocrystal Surface Modification



Note: not to scale

- Capping agents
  - improve dispersibility
  - Increases compatibility
  - Reduces surface effects
- Long capping agent
  - Low/loose packed surface coverage
- Short capping agent
  - High/dense packed surface coverage
- Functional capping agents
  - Crosslink into polymer
  - Acrylic, epoxy, other…
- Multiple capping agents
  - Can control ratio of capping agent to crosslinker density

Capping Variations and Impact on RI – PixClear® 4pack

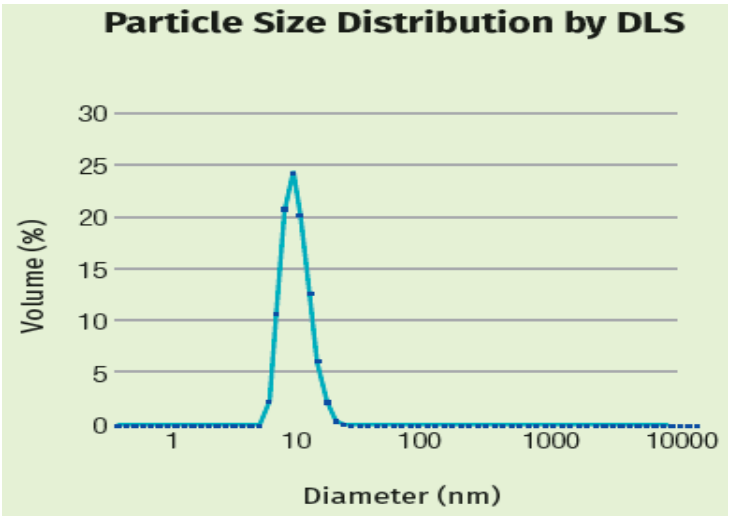


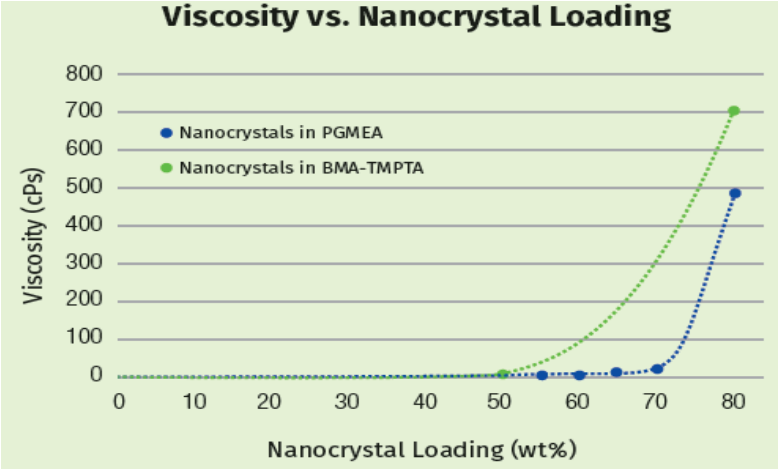
- For the cross-linking materials: PCPR has higher acrylic cross-link capping resulting in greater substrate adhesion, hardness and better performance with processing chemicals
- PCPB-2 has higher dispersibility capping leading to higher RI nanocomposites

*RI at 450 nm with up to 90wt% loading measured by ellipsometer using base polymer with 1.58 RI at 450 nm

ZrO_2 Nanocrystal Dispersion Properties

- Monodisperse with 99.99% of particle diameter < 30nm
- Viscosity remains low over 50-75wt% loading range
- Tunable refractive index and formulation options derived from suite of capping agents
- Long shelf life = 6+ Months

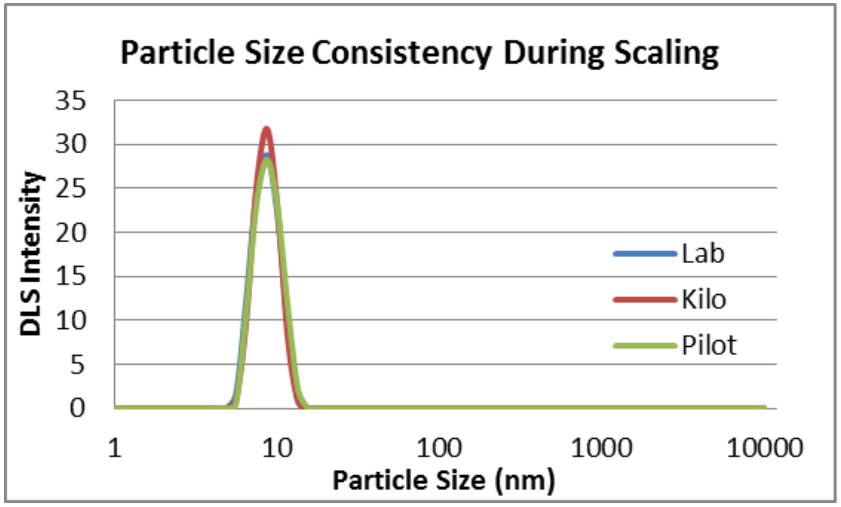


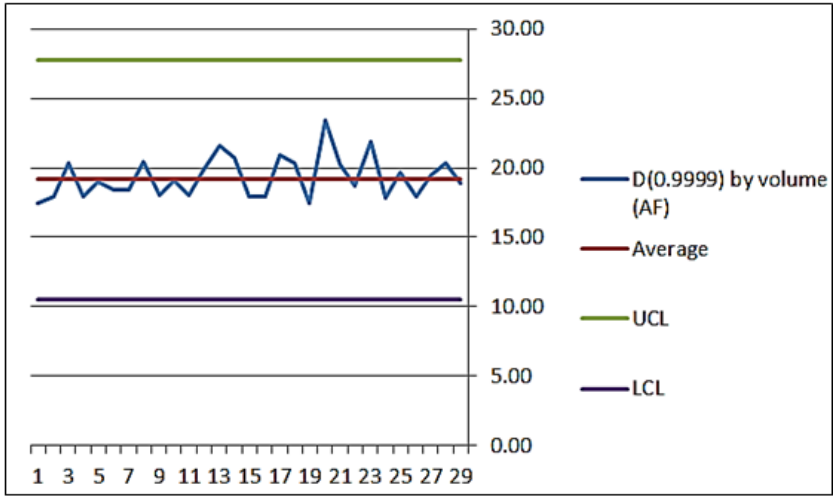


Scaled Manufacturing

- Frost & Sullivan 2017 Manufacturer of The Year
- Precursor –Readily available, multiple vendors
- Equipment – Standard equipment and processes in custom configurations. Available from multiple suppliers
- Process – Uses standard proven wet chemistry processes
- Technology – Very repeatable and robust with process recipes transferred from engineering to pilot scale
- Cost –Competitive total costing in target markets
- Environmental Compliance – Fully TSCA and REACH compliant

Consistent Batch Quality

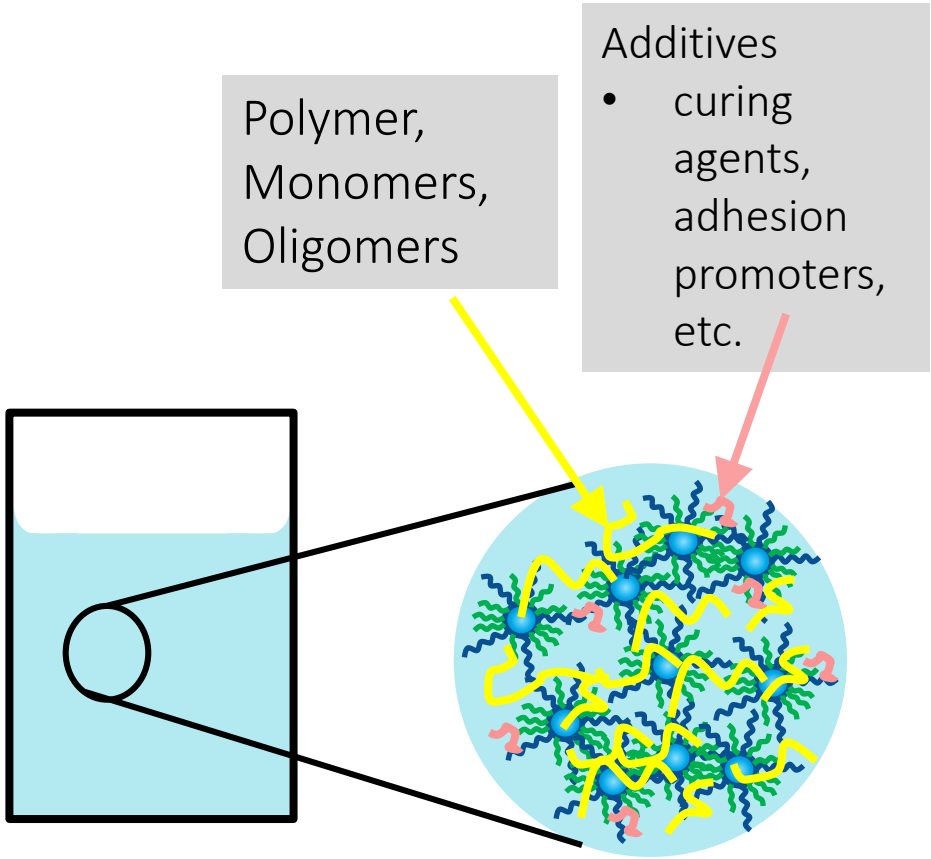




High RI Formulations

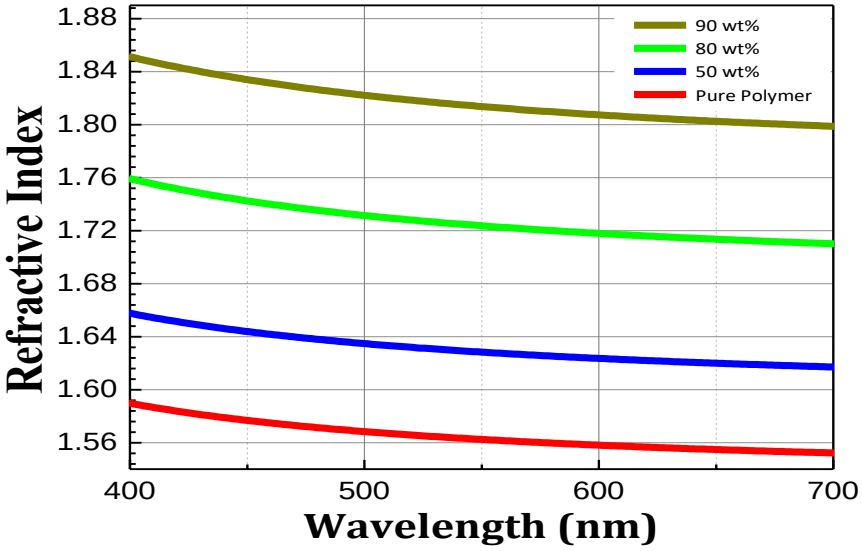
Nanocrystal Dispersion → **Formulation** → Deposition Method → Device with Nanocomposite

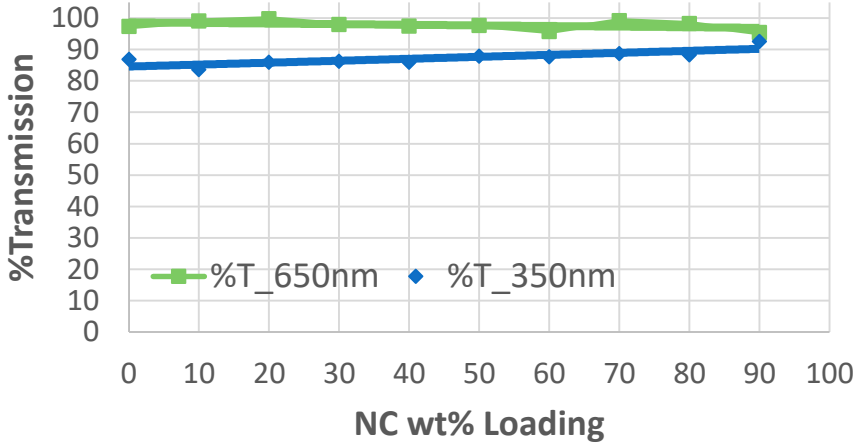
- Curable liquid with capped nanocrystals + polymer/monomer + additives
- Solvent free or solvent containing
- UV curable
- Transparent or with scatterers
- Need to meet desired requirements – viscosity, shelf life, cure conditions, purity, surface tension, uniformity, repeatability …
- Compatible with formulation manufacturing

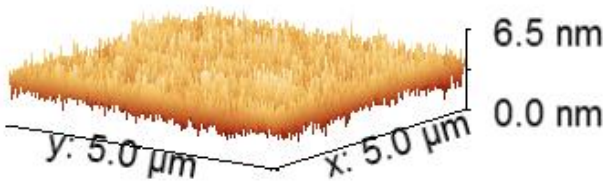


Characteristics of HRI Enabled Materials with ZrO_2 nanocrystals

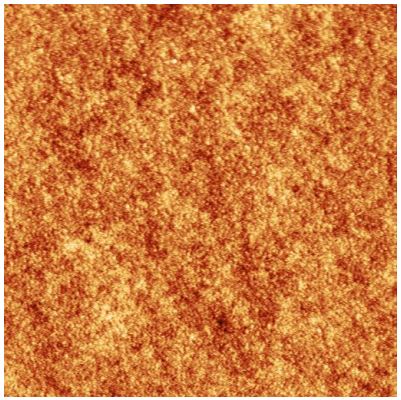
High RI, High Transmittance, and Smooth Surface





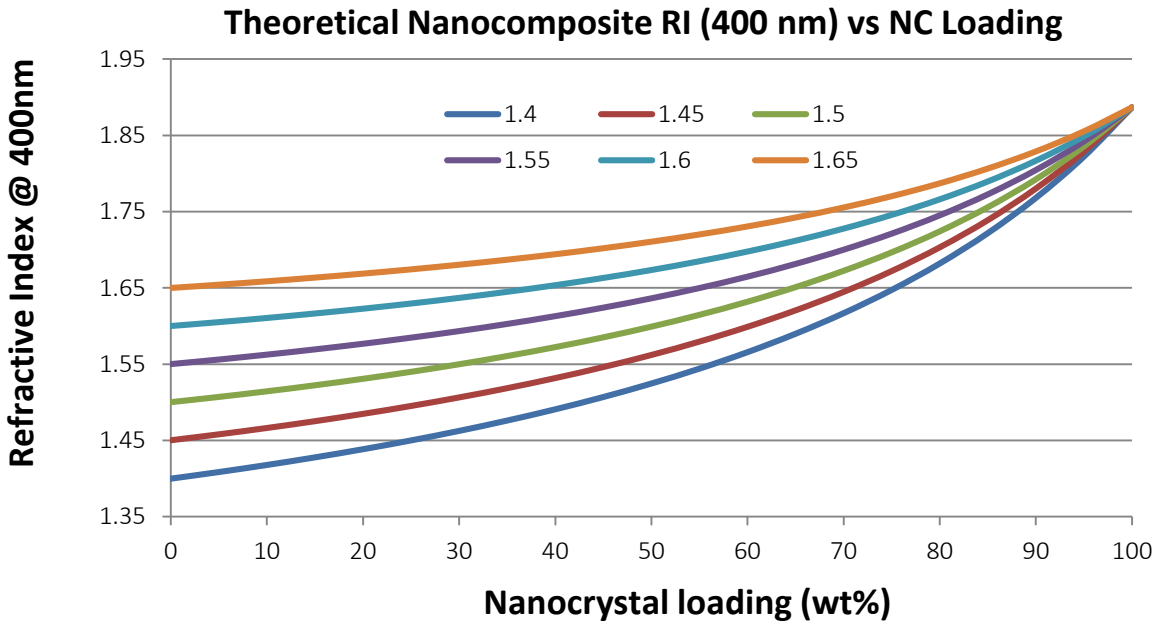


5 x 5 um scan area



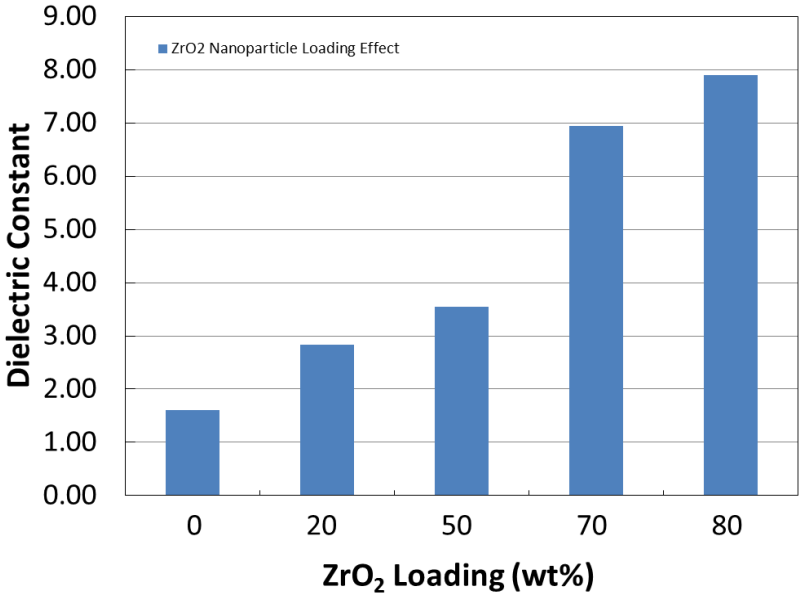
Ra = 0.529 nm
RMS = 0.665 nm
Rz = 6.455 nm

Calculated Nanocomposite RI

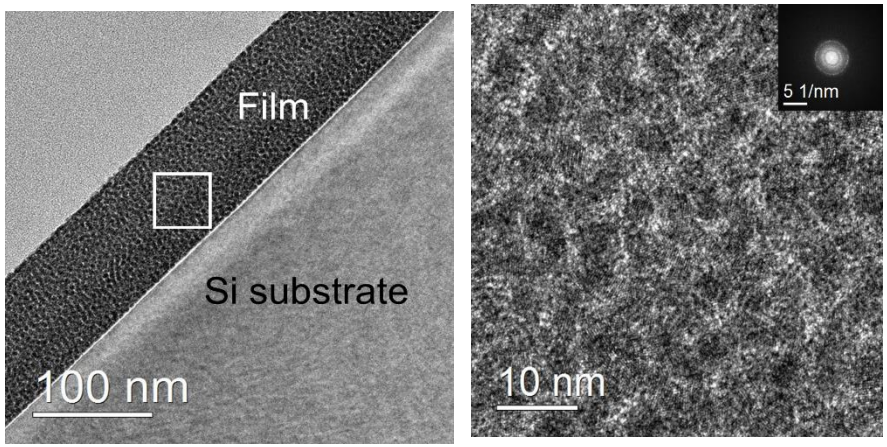


- RI increase depends on the starting RI of the polymer
  - Each line represents a different base polymer with RI at 400nm listed in the legend
- Composites converge on theoretical maximum of 1.9 RI
  - RI of pure capped nanocrystals at 400 nm

Other Properties: High Dielectric Constant Film



Dielectric Constant of ZrO_2 Film



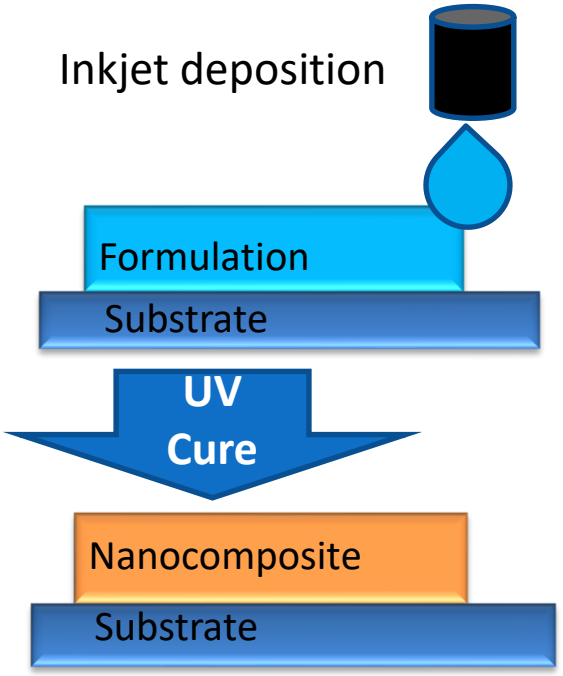
TEM Images of ZrO_2 Film and Nanocrystal

- Bulk ZrO_2 has a dielectric constant between 13 to 24.
- At loading > 50wt% have dielectric constants above common dielectric materials (e.g. SiO2 = 3.9) can be attained
- A 2-µm film has high transparency (> 95%) over the entire visible light range, uniform nanocrystal dispersion in the film.

Nanocomposite Deposition

Nanocrystal Dispersion → Formulation → Deposition Method → Device with Nanocomposite

- Inkjet printing
- Slot die Coating
- Imprint Lithography
- Spin-coat
- Screen printing
- Dispense
- Spray coating
- Others



Ink Jettable High RI Nanocomposites

- Ink-Jet Printing is a key technology for OLED Display
  - Opens major opportunities based on integration with customer manufacturing processes
- Ink formulation with ZrO_2
  - Long pot life without clogging
  - Good uniformity for 'blanket' films
  - Testing larger scattering particles and ZrO_2 together
- Deposition on glass substrates
  - Uniform films
  - Test patterns
  - Drop arrays

FujiFilm Dimatix DMP 2800

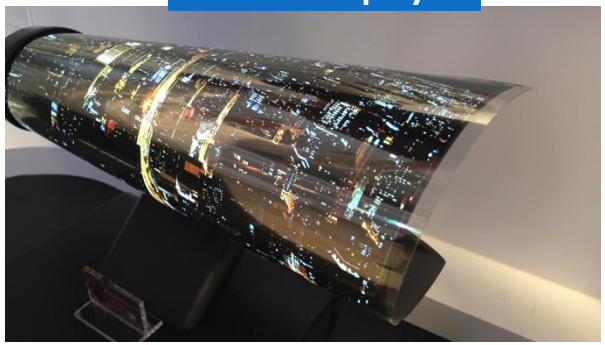
Enabling innovative devices with Nanocomposites

Nanocrystal Dispersion → Formulation → Deposition Method → Device with Nanocomposite

- High refractive index needed for efficient light extraction
- Solution processable needed to meet cost and quality targets
- Displays - High RI ZrO2 enable significantly higher light extraction, higher brightness, improved operating efficiencies for OLED, LCD and reflective displays
- OLED lighting - increases lumen-per-watt by 100%+ in OLED lighting with a high RI internal light extraction layer
- LED lighting – delivers 5-10% lumen gain in LEDs by increasing the RI in silicone
- Less waste heat
- Longer lifetime

LED, LCD,QD, and Reflective Displays

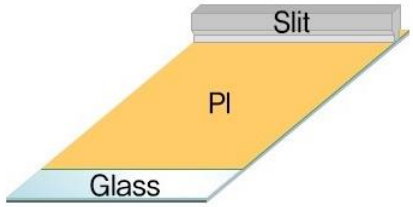
OLED Display

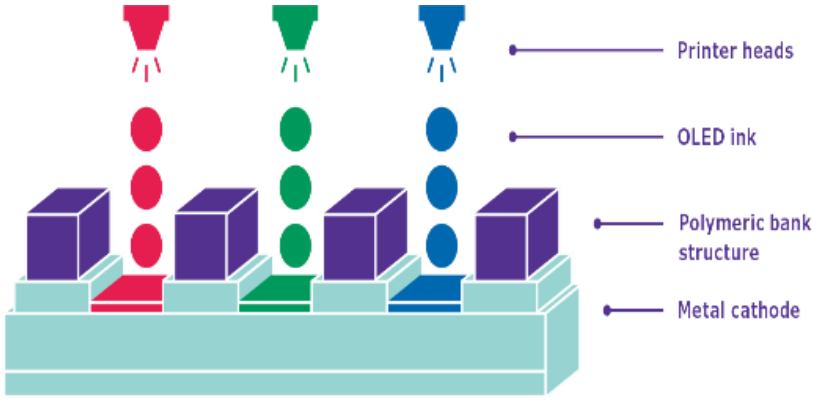


OLED Lighting

LED Lighting

Process Changes Occurring in OLED Display





Process changes (Vacuum ➔ Solution process)

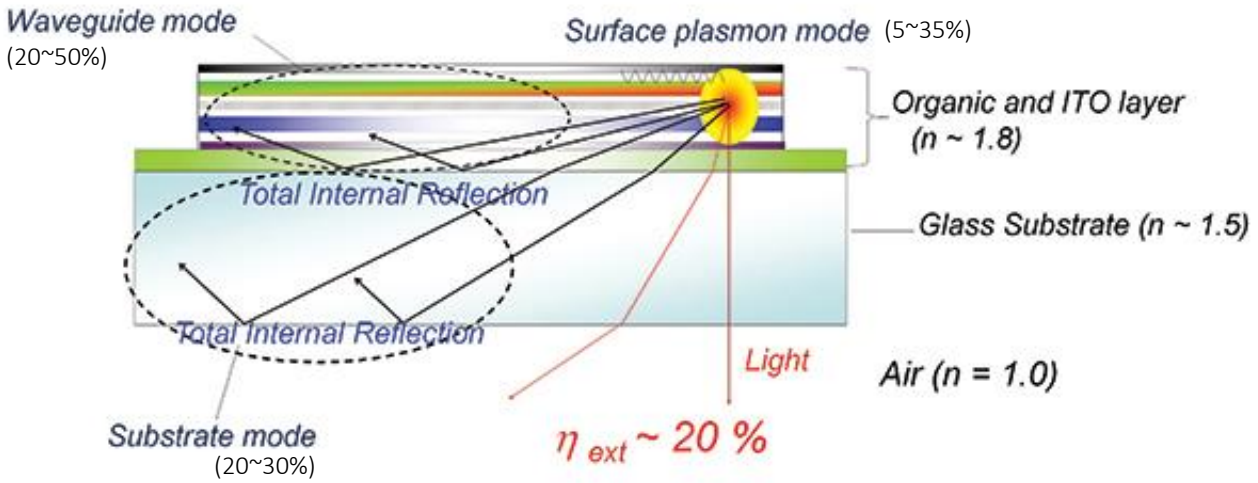
	Vacuum	Solution
Substrate	Glass	Soluble PI
OLED	Evaporation	Polymer, Inkjet etc.
Encapsulation	Inorganic, getter	Polymer hybrid, Inkjet etc.
Polarizer	-	Coated process

OLED Light Extraction Problem

- Total Internal Reflection traps most of the light in the device
- Different light extraction schemes vary in how and where light is redirected
- SPM and substrate mode can be reduced by corrugation and surface control, respectively
- Waveguide mode (ITO/substrate interface) is where light should be redirected for maximum benefit

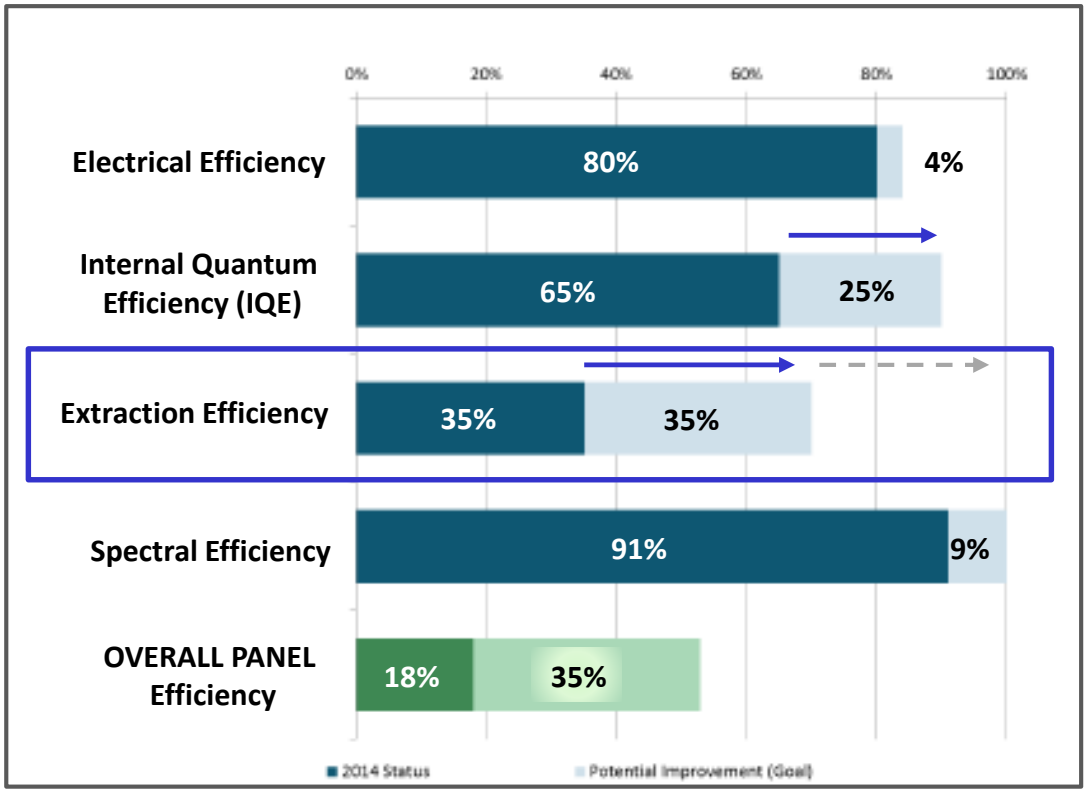
$$\eta = \eta_i \times \eta_e \times \eta_{ext}$$

η_i : internal quantum efficiency
η_e : electrical efficiency
η_{ext} : light extraction efficiency



Potential Improvement

Light Extraction Technology is Important to achieve High Panel Efficiency



(The goal corresponds to an LER(Luminous Efficacy of Radiation) of 360 lm/W and a panel efficacy of 190 lm/W.)

OLED Lighting Panel Loss channels and Efficiencies

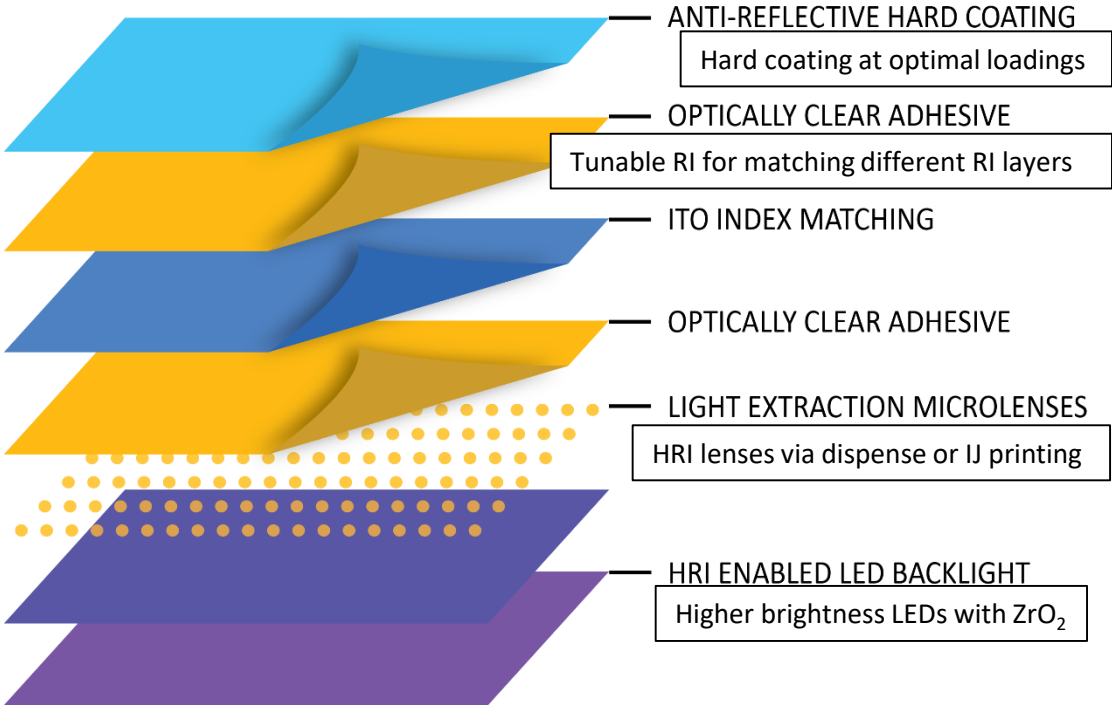
Source: Solid-State Lighting R&D Plan by Department of Energy (June, 2016) DOE/EE-1418

- Electrical & Spectral Efficiency
  - Almost developed
- Internal Quantum Efficiency
  - TADF, Phosphorescence for blue
- Extraction Efficiency
  - Optical material & structure design
- Similar efficiency improvement expected for OLED display

Improved light extraction increases display efficiency and the preferred method is solution processing

Display Applications

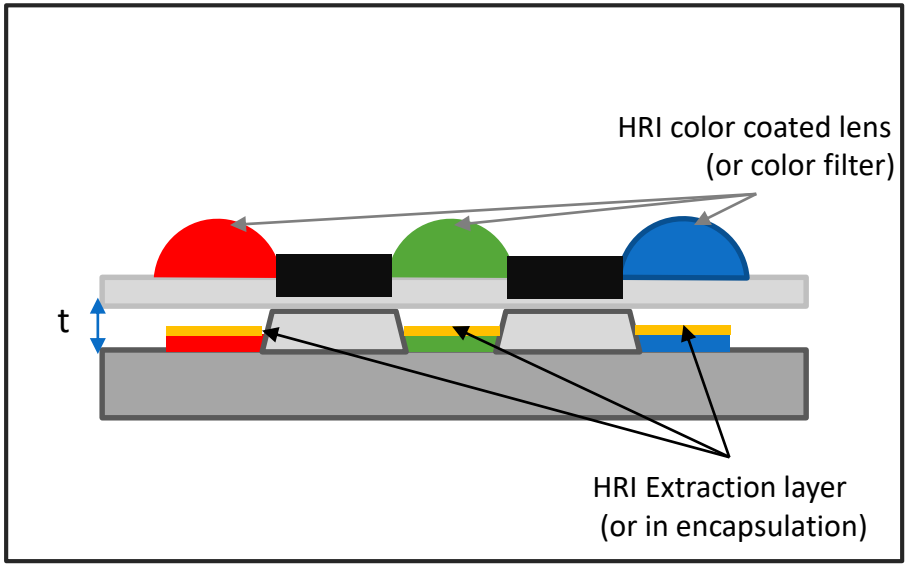
- Flexible or rigid substrate
- Solution processable
- Inkjet compatible
- Top or bottom emission display
- 95% transparency
- Improved scratch resistance



Microlenses approach for OLED Display Light Extraction

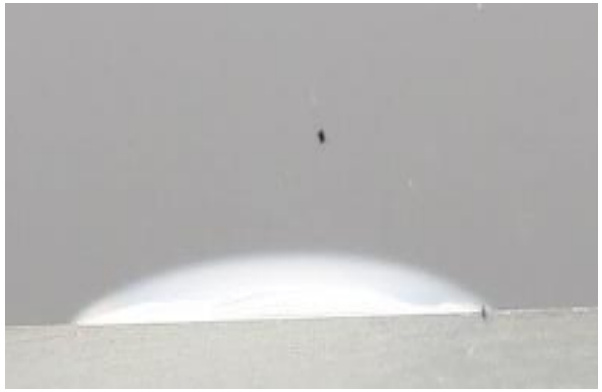
- Drawbacks of microlenses such as crosstalk or back-scattering can be addressed though optimized lens design and colored lens structures (Lens per pixel)
  - Distance “t”
  - Black matrix
  - Color coated HRI lens (or HRI lens on CF)
- Refractive index modulation and HRI gives greater design freedom through higher focusing power and increased light extraction
  - Capping layer
  - Encapsulation
- Scalability and simple fabrication of lenses can be achieved through solution processable HRI material

Concept with soluble HRI material



Creating Lens Structures to Dramatically Increase OLED Display Efficiencies

Side Profile: θ = 54°



(On soda lime glass)

Side Profile: θ = 26.0°

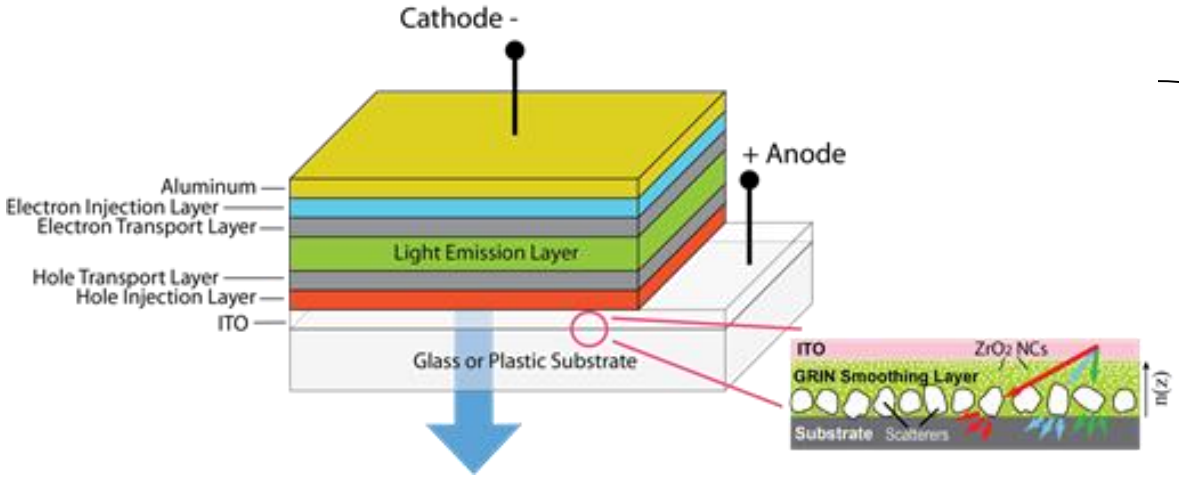
Uniform Lenses with HRI Formulation

Structured Substrate Approach

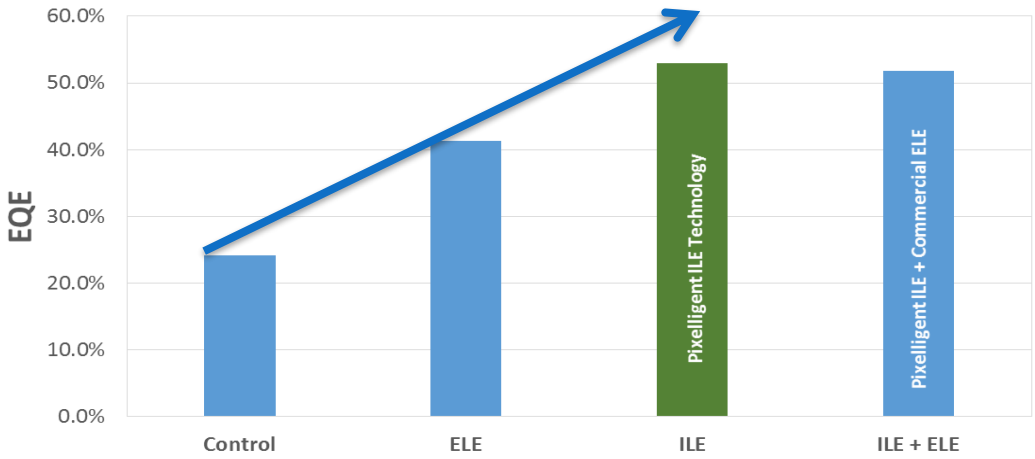
Smoothing layer deposited over structured substrate to form lens-like structures

HRI smoothing layer

OLED Lighting Applications

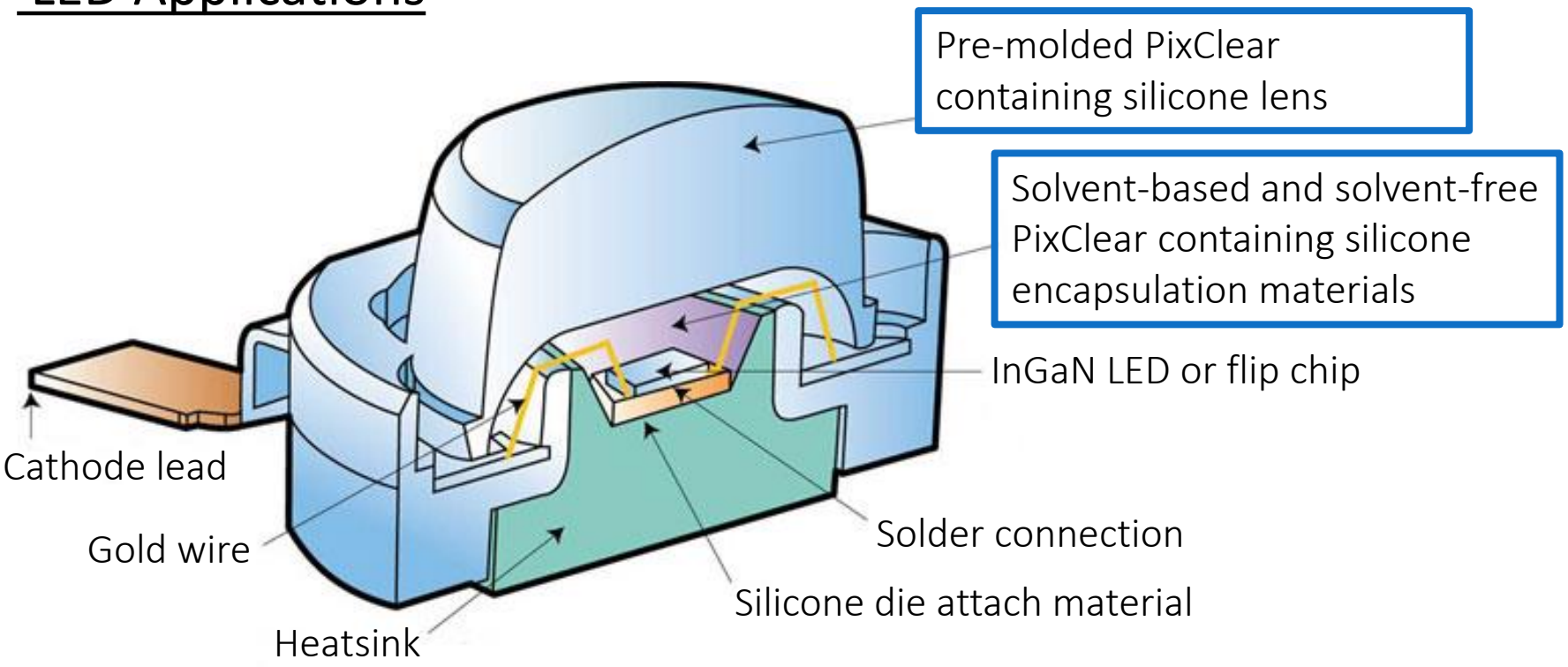


PixClear® Gen 1 internal light extraction ("ILE") materials provide a smoothing layer. Also included in the scattering formulation.



PixClear® Gen 1 ILE materials provide more than 100% increase in light output compared to control

LED Applications



- PixClear® silicone nanodispersions increase Refractive Index of Silicones from 1.4 to 1.65 to better match the index of LED chip and delivering lumen gains of 5-10%

Material Properties for Display Applications

- Solution processable materials are low cost, easier to deposit

BUT:

- Have to achieve high level of performance
  - high RI
  - low O_2 and moisture permeability
  - solvent free and low viscosity preferred
  - high level of reliability
  - low outgassing
  - low dose UV curing
  - smooth surface
  - low particle defects
  - no pin hole

Achieving all requirements simultaneously is challenging!

Summary

- Pixelligent's innovation in nanocrystal dispersion enables high performance nanocomposites
  - High RI, transparent, solution processable
- Compatible with many deposition methods and device structures
- Results in brighter, more efficient Displays, and increases light output of OLED and LED lighting

Thank you

For Product Information, please visit:
http://www.pixelligent.com/products/

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

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