The Clear Solution®

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Acknowledgements

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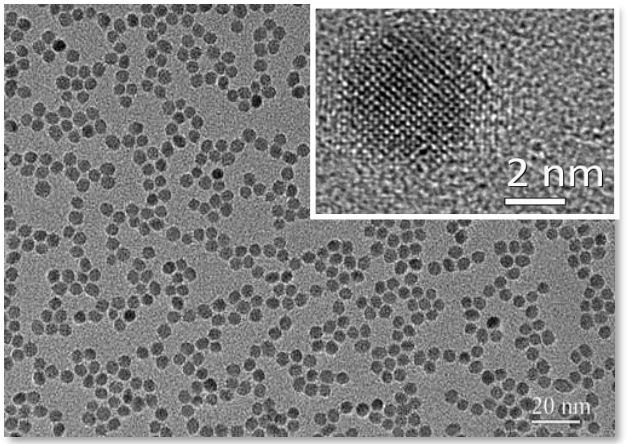
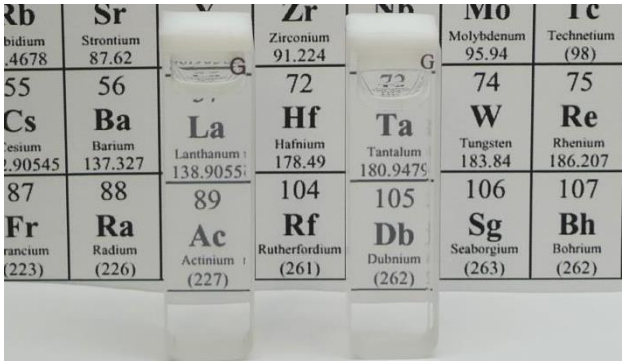
Technology Leader in High Refractive Index Materials

- ZrO_2 Nanocrystal Dispersions
- Best Dispersions Available
  - 5nm-10nm Spheres
  - Fully Uniform
  - High Loadings (>80wt%)
  - 95% Transmittance
  - High RI >1.8
  - Broad Compatibility
- Highly Scalable Process
- Strong IP Position 57 issued and pending patents



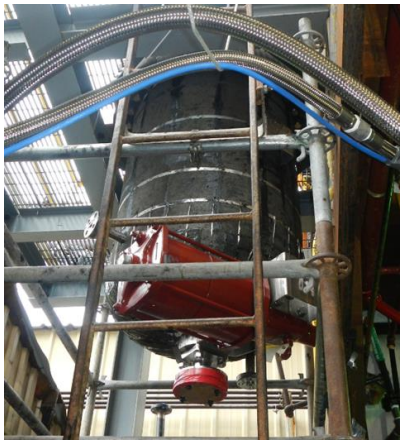


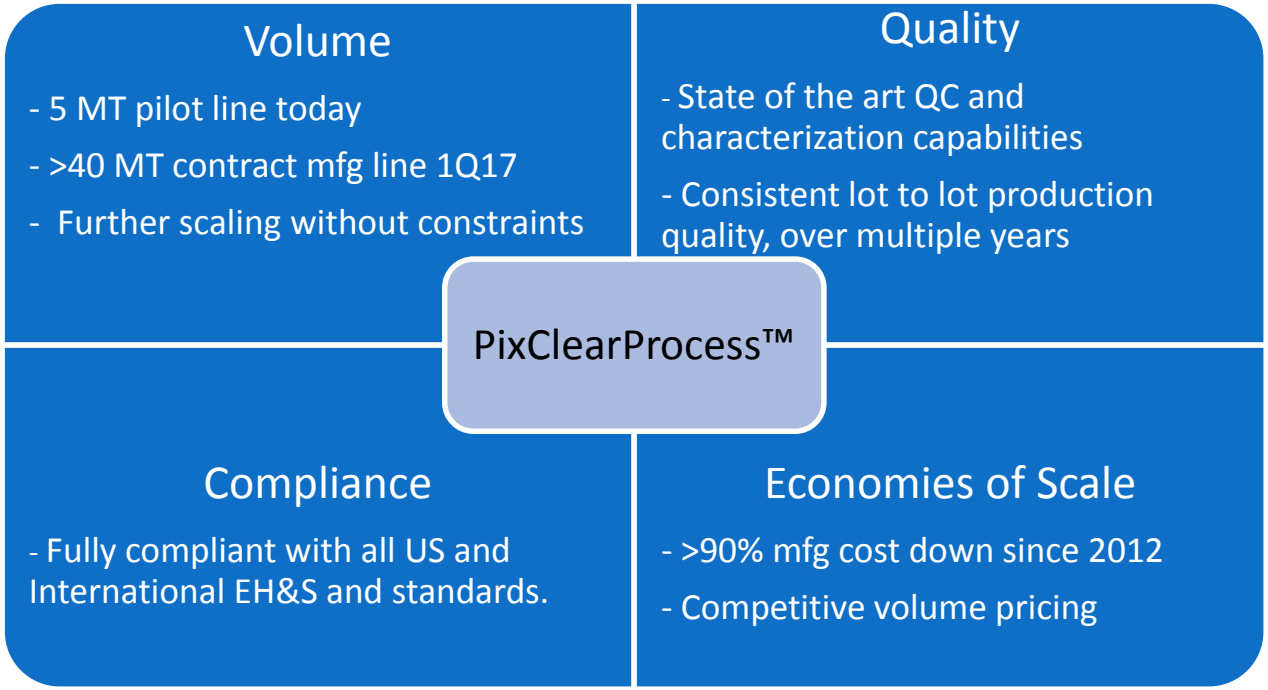
Left: 50wt% ZrO2 Nanocrystals | **Right:** Pure Solvent

Pixelligent's Scaled Manufacturing

ZrO2 Nanoparticle	•Same ZrO2 nanoparticle for all products
Capped ZrO2 Nanoparticle	•Application specific surface modification •Same equipment and process for all products
Nano Dispersions and Formulations	•Broad materials compatibility •Wide range of applications

Frost & Sullivan 2017 Manufacturer of The Year



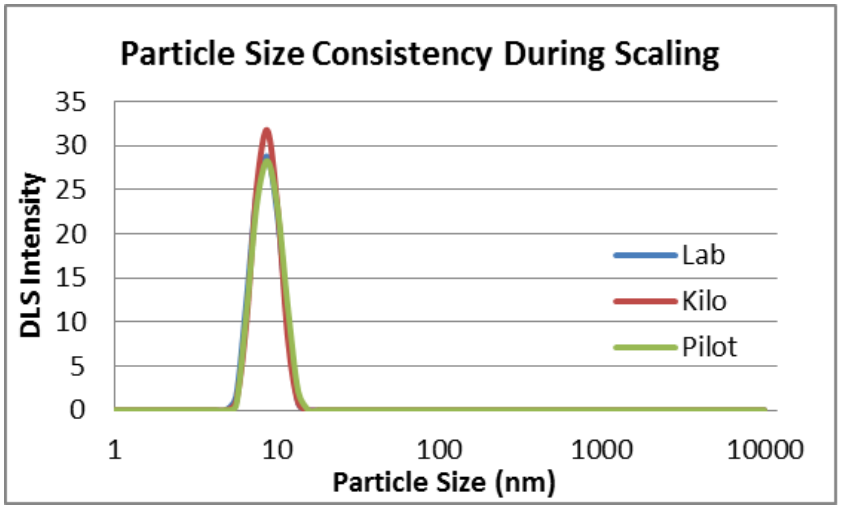


Why Pixelligent has scaled complex nanomaterials where others have failed:

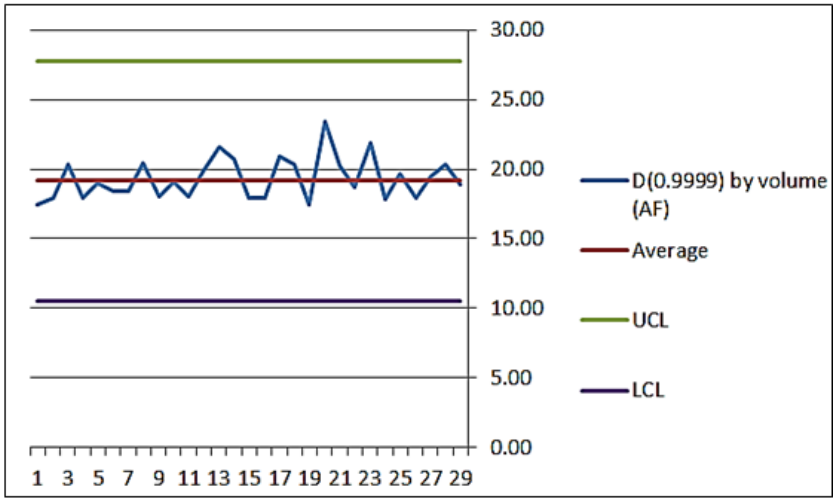
Focus on one material system at a time	**Experts in nanoparticle synthesis and surface chemistry**
Portfolio of proven surface modifiers	**Fully integrated product development and manufacturing processes**

Robust Process Control and Analytics

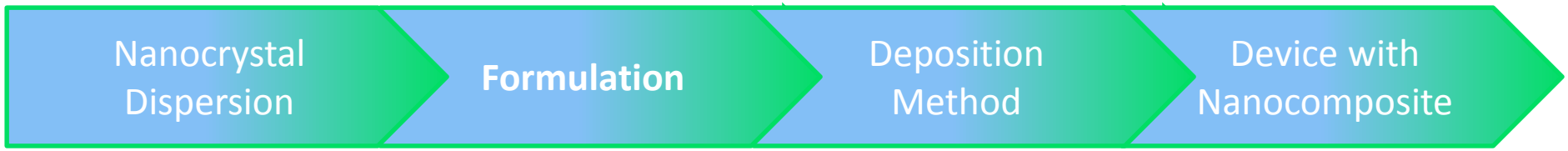
- Process Control – Siemens based custom process control and monitoring system
- Analytics – Multiple tools measuring particle size, dispersion quality, and purity ie. DLS, UV-VIS, TGA, GC, viscometer, etc.



Consistent Batch Quality



Pixelligent's technology needed at all manufacturing levels



Nanocrystal Dispersion	Formulation	Deposition Method	Device with Nanocomposite
Pixelligent's innovation in nanocrystal dispersions enables …	New formulations that work with existing …	Deposition Methods that are already scaled and becoming increasingly important to create…	Devices with Nanocomposites that are more efficient, simpler to make, or couldn't be made with traditional materials and methods

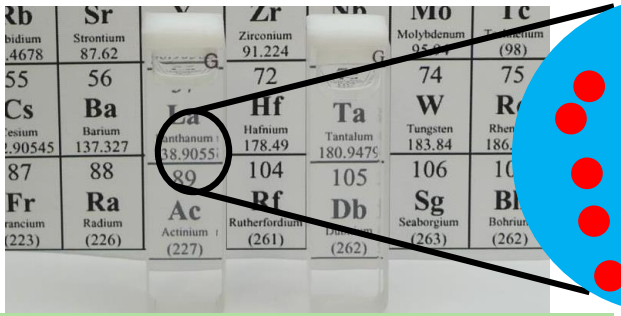
Pixelligent's innovation in nanocrystal dispersions enables …

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

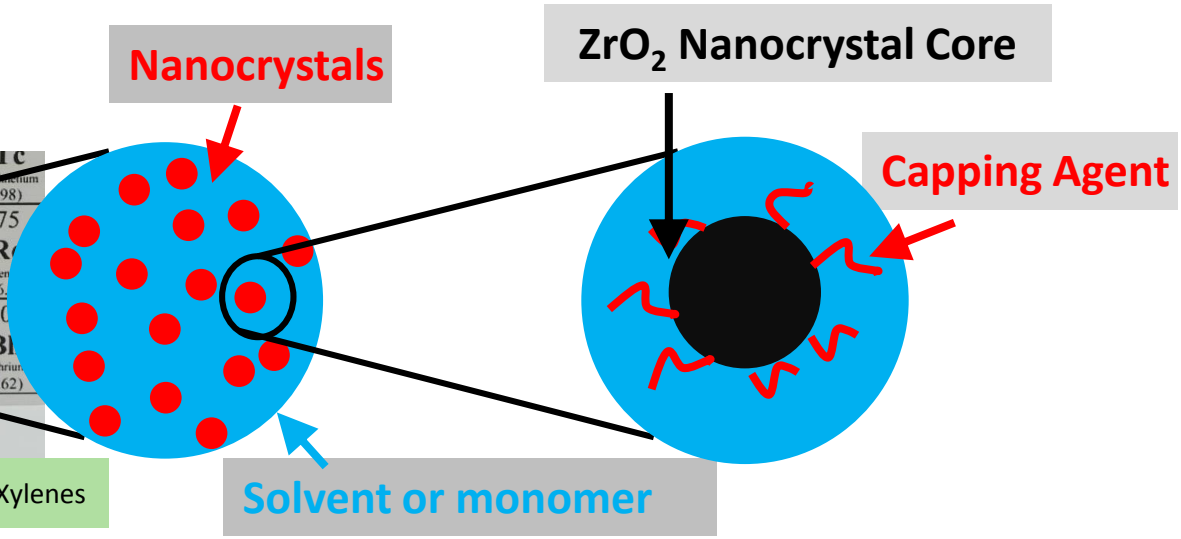
- Capped nanocrystals dispersed in solvent or monomer
- Many choices of capping agents depending on solvent/polymer
- Multiple capping agents on same nanocrystal – cross linkers + dispersion

- Best dispersion – no aggregation or settling
- Stable for years
- Low viscosity increase
- Transparent
- Scaled manufacturing – uniform and repeatable

Pixelligent Product – Nanocrystal Dispersions



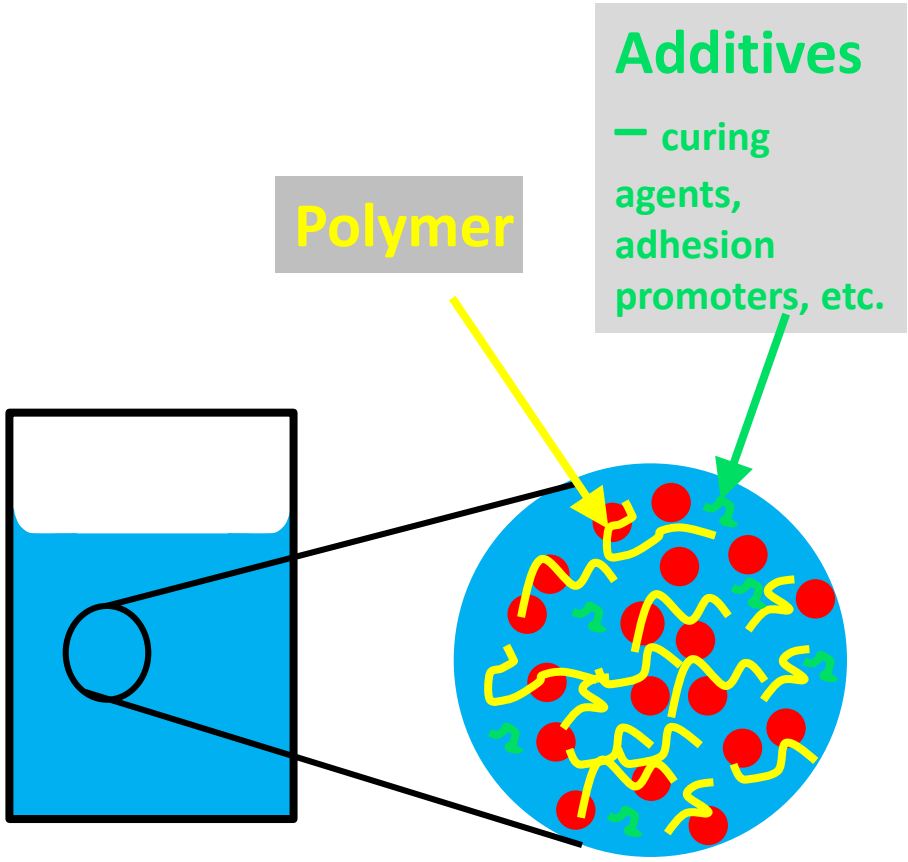
Left: 50wt% ZrO2 Nanocrystals | **Right:** Pure Xylenes



New formulations that work with existing …

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

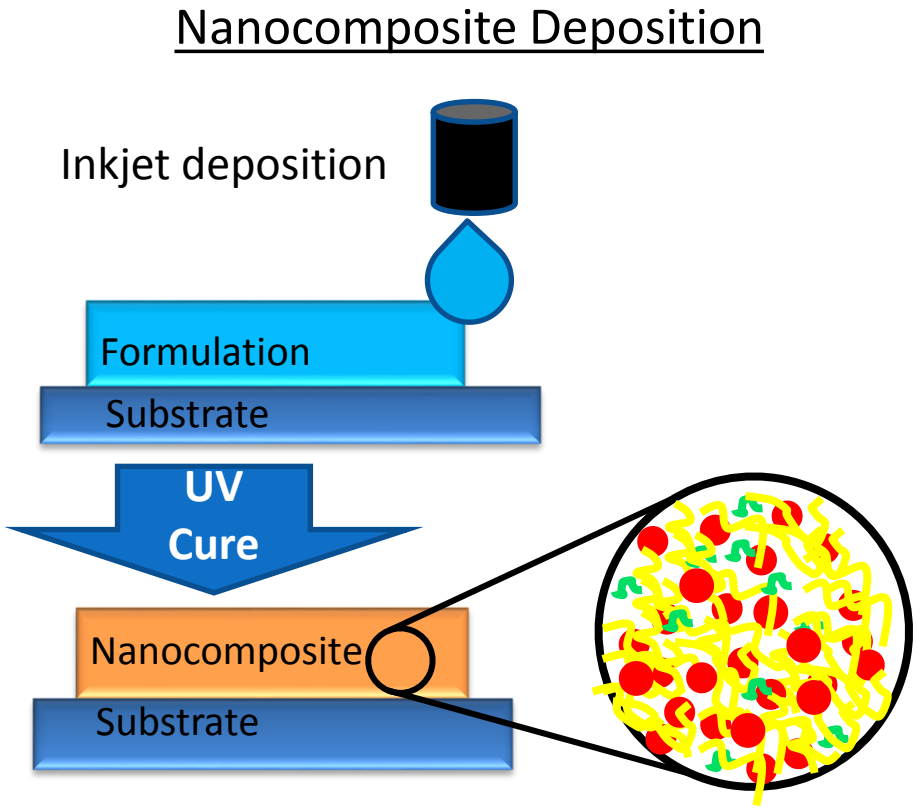
- Curable liquid with capped nanocrystals + polymer/monomer + additives
- Need to meet desired requirements – viscosity, shelf life, cure conditions, purity, surface tension, uniformity, repeatability …
- Compatible with formulation manufacturing



Deposition Methods that are already scaled …

Nanocrystal Dispersion → Formulation → Deposition Method → Device with Nanocomposite

- Inkjet printing
- Slot die,
- Imprint Lithography
- Spin-coat, screen printing, dispense, spray coating, and others

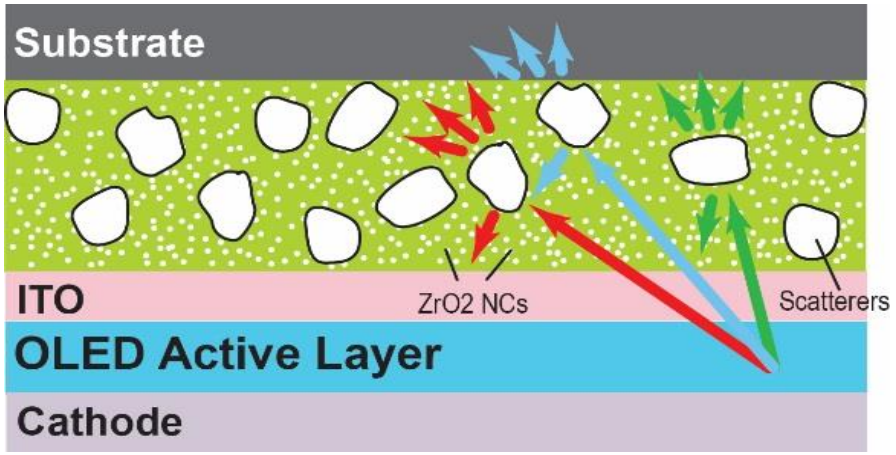


Enabling innovative devices with Nanocomposites

Nanocrystal Dispersion → Formulation → Deposition Method → Device with Nanocomposite

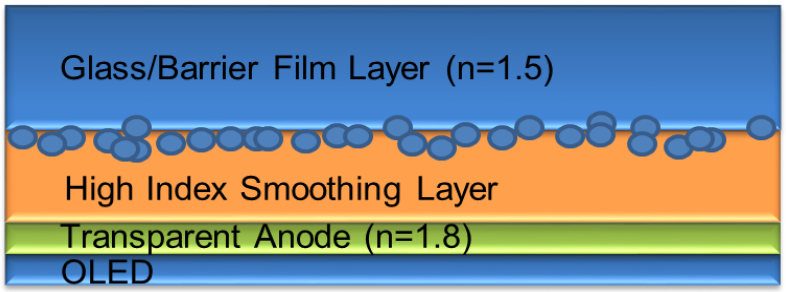
Example: Optoelectronics - OLED

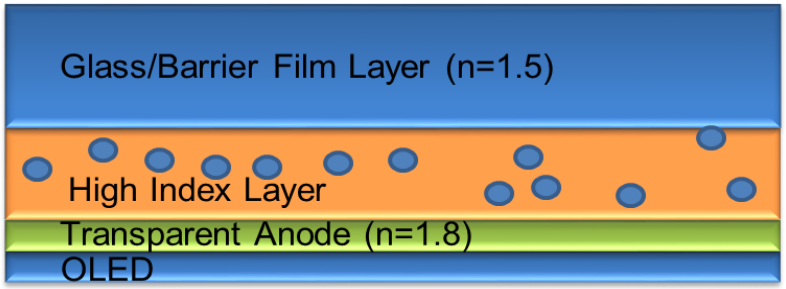
- High refractive index needed for efficient light extraction – solution processable needed to meet cost and quality targets
- Less waste heat
- Longer lifetime
- Eliminate other components = lower overall cost and simplified manufacturing

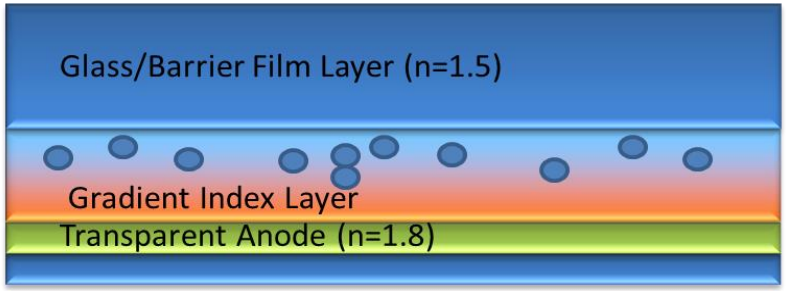


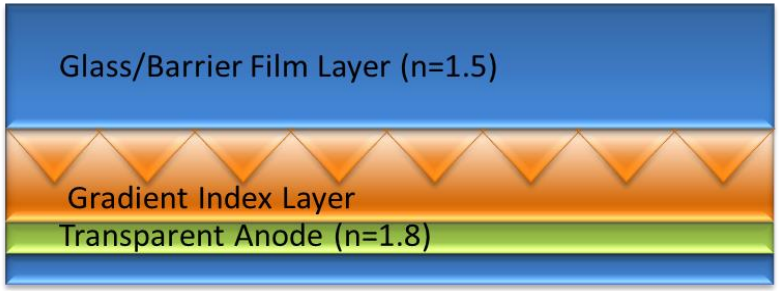
OLED Stack with extraction layer: scattering particles, embedded in a high refractive index nanocomposite. The green, blue, and red rays correspond to light that naturally escapes, is totally reflected at substrate/air interface, and is totally reflected at ITO/substrate interface, respectively. The reason why a high refractive index binder is needed is because it allows the high angle light (red rays) to couple into the extraction layer and then get to the scattering particles where the light can be redirected

Pixelligent's OLED Light Extraction Roadmap





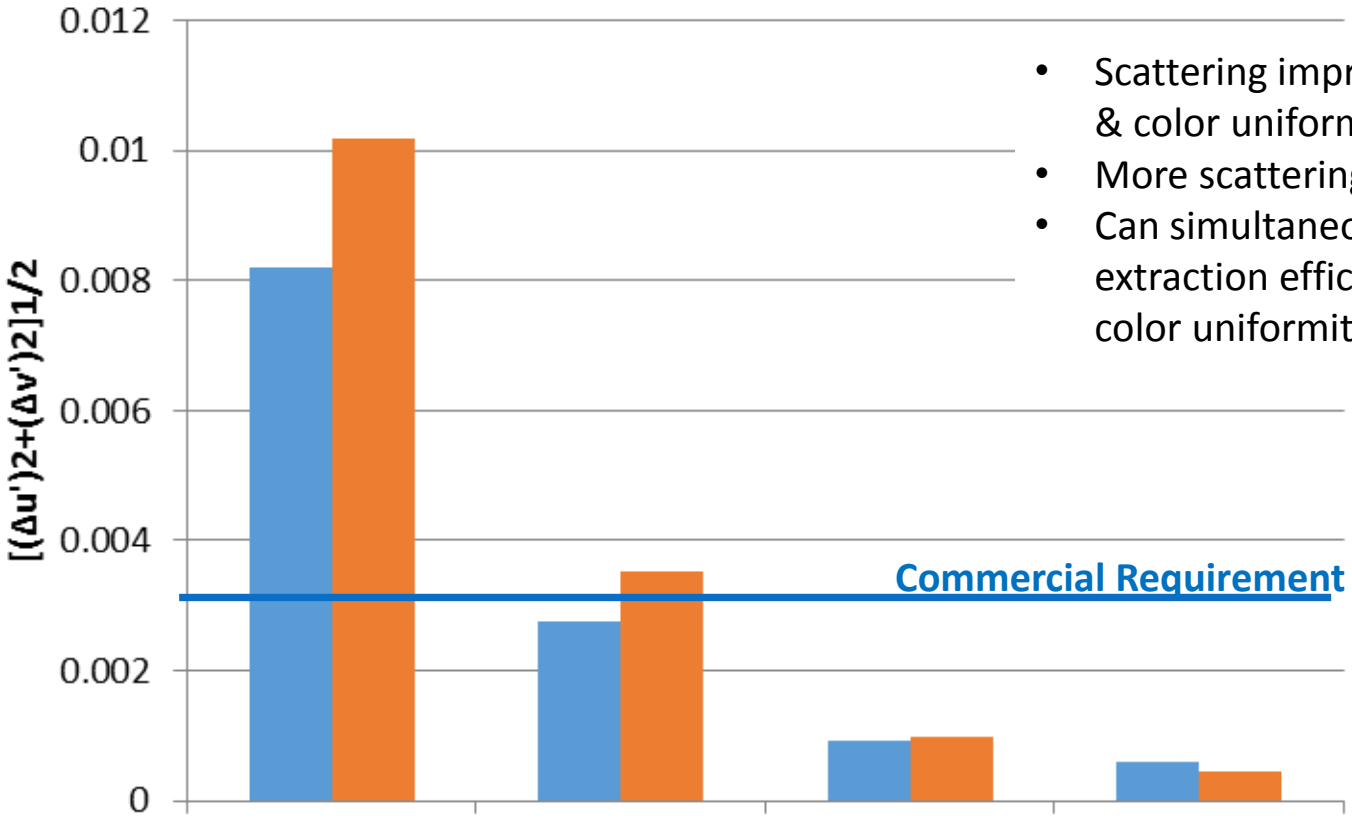




OLED Lighting Will Need Internal HRI Light Extraction

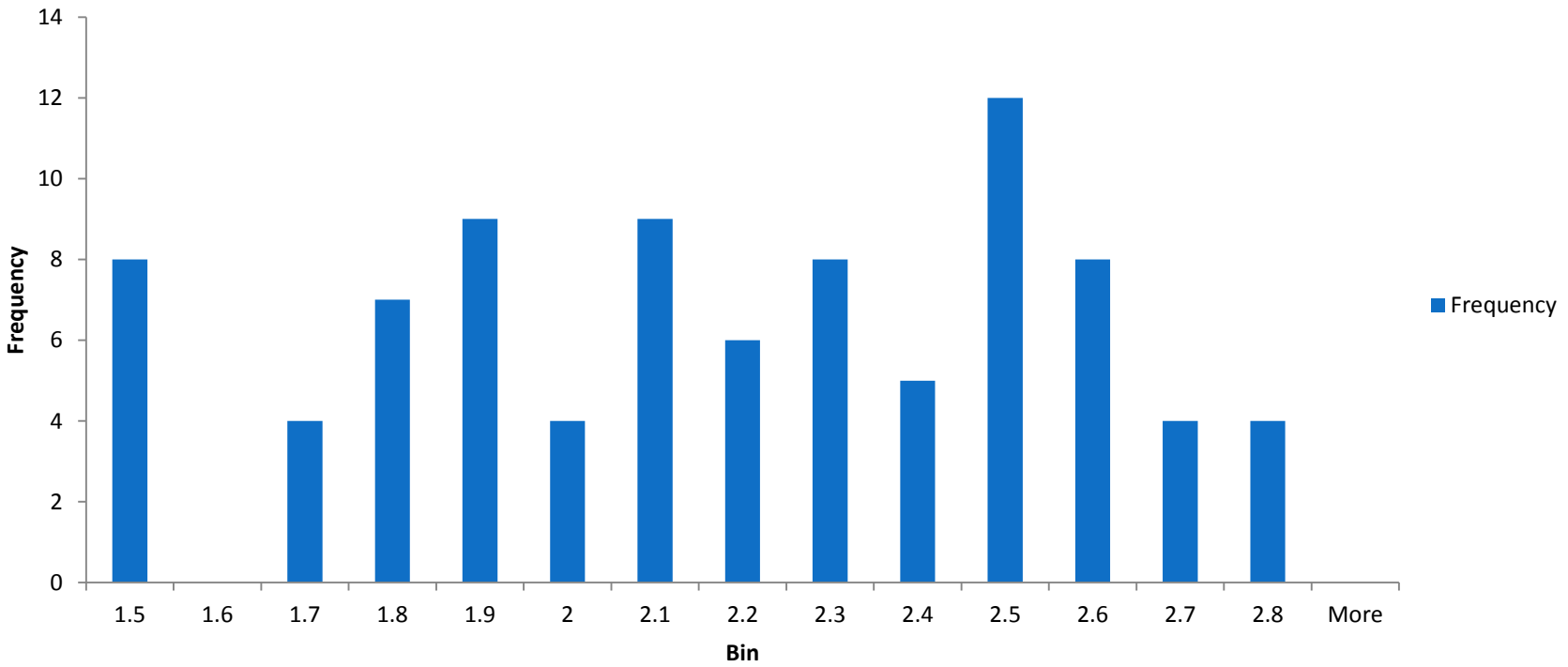
- HRI light extraction offers highest efficiency
- Two issues
  - Cost
    - Simplify device- fewer layers, fewer deposition steps
  - Manufacturing – yield and lifetime
    - Introduction of defects that cause shorts
    - Poisoning of the device

Gen 2 Color Variation with Angle



- Scattering improves light extraction & color uniformity
- More scattering = more uniformity
- Can simultaneously achieve high extraction efficiency and excellent color uniformity

Gen 2 EQE Improvement > 2.5X



- 88 Gen 2 devices – solution processed high index layer with scatterers
- Lots of variation – we think the main reason is due to defects – particles deposited from "dirty" environment cause shorts
- Defects lower efficiency but higher efficiency results are real

Other Approaches

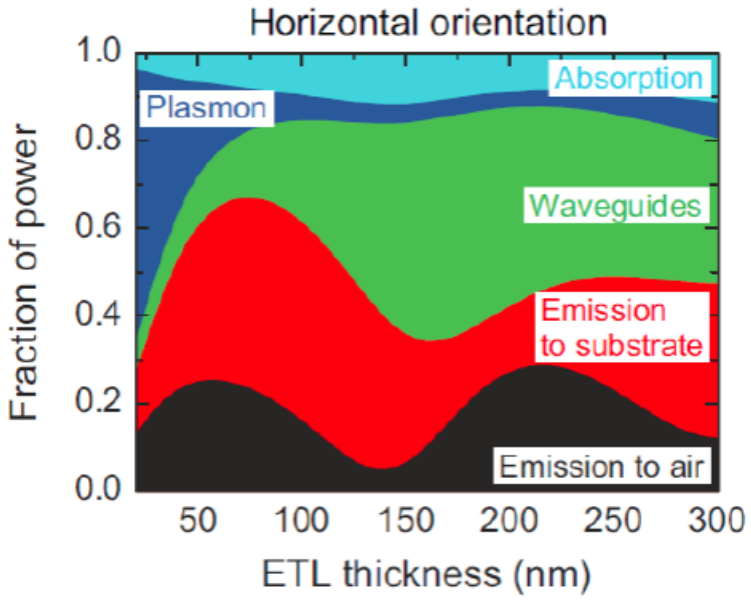
- Internal HRI light extraction is compatible with many other approaches and device structures
  - Silver nanowires
  - Directed emitters
  - Corrugated substrates
- All approaches need to be analyzed with internal HRI light extraction and multi-layer devices

Silver Nanowires

- Offer important advantages
  - Low cost
  - Roll to roll and/or solution processing
  - Flexibility
  - Light extraction – favors fewer larger nanowires
- Challenges
  - Lifetime
  - Yield
  - Uniformity – favors more smaller nanowires

Directed Emitters

- More light emitted in forward direction – relatively more in substrate and air modes
- Still need internal HRI light extraction
- Need to analyze with multi-layer device and include color uniformity with angle



M. Thompson, Electrophosphorescence for Solid-State Lighting, 2017 OLED Stakeholder Meeting

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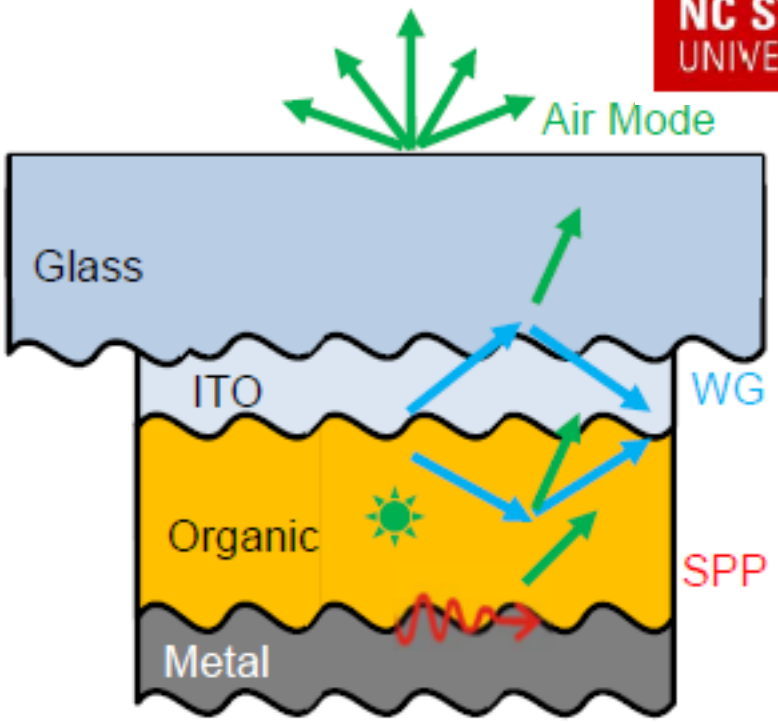
Corrugated Substrates

- Scatters light and suppresses plasmons
- Enough scattering for optimal light extraction and color uniformity with angle?
- Manufacturing concerns
- Need to analyze with multi-layer device



F. So, Light Extraction in OLED with Corrugated Substrates, 2017 OLED Stakeholder Meeting

Summary

- Pixelligent's innovation in nanocrystal dispersion enables innovative devices with nanocomposites
- For OLED lighting – solution processable internal HRI-LE
- OLED lighting will need HRI-LE – reduces cost, need to solve yield and lifetime
- Compatible with many other methods and device structures
- Analysis needs to consider HRI-LE, multi-layer devices, and color uniformity with angle