pixelligent

The Clear Solution®

Ink-Jet Printing of High-Index Zirconia Nanocomposite Materials

Dr. Peter Guschl

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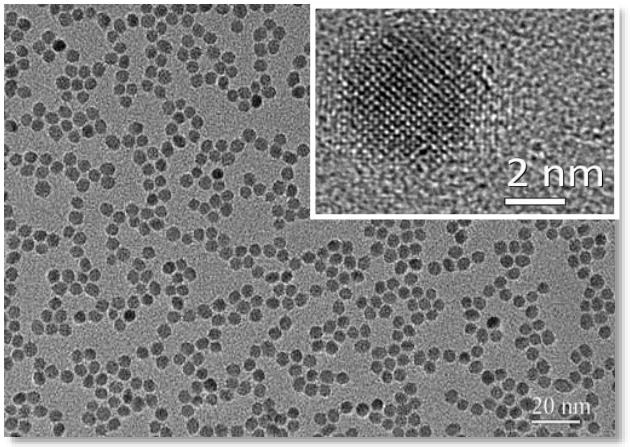
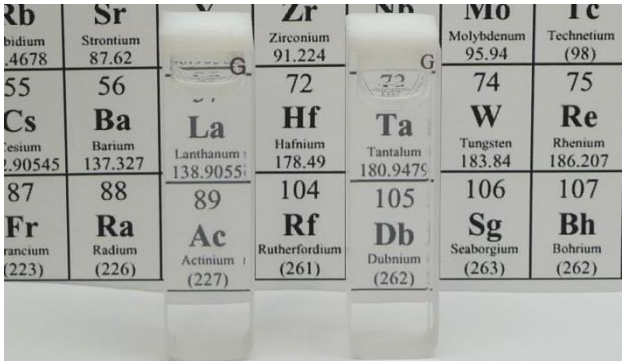
Technology Leader in High Refractive Index Materials

- ZrO_2 Nanocrystal Dispersions
- Best Dispersions Available
  - 5 nm Spheres
  - Fully Uniform
  - High Loadings (> 80wt%)
  - 95% Transmittance
  - High RI > 1.8
  - Broad Compatibility
- Highly Scaled Process (40 MT)
- Strong IP Position 43+ issued and pending patents

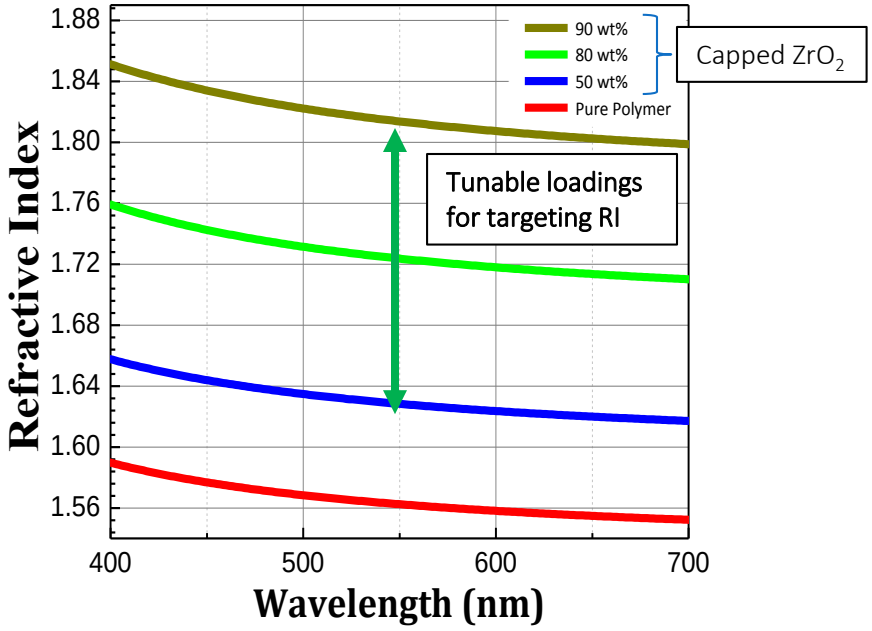




Left: 50 wt% ZrO2 Nanocrystals in Solvent | **Right:** Pure Solvent

PixClear Nanocomposite Performance

Measured Data for 3 Micron Film in Acrylic Polymer

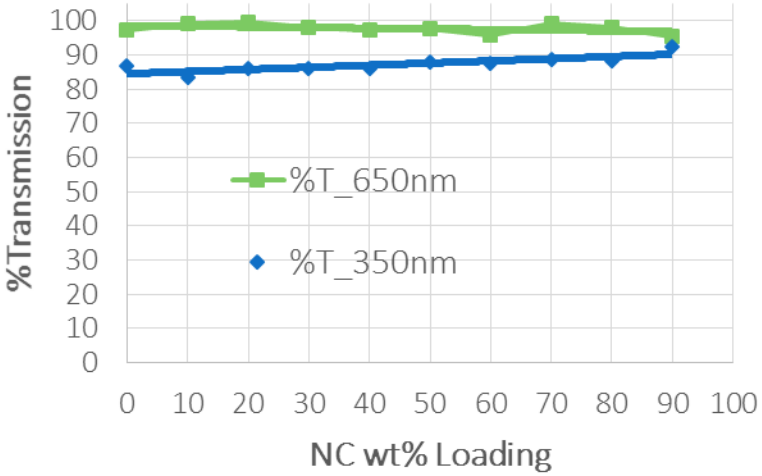


Nanocomposite with Capped ZrO_2 in Polymer Binder

Moderate Loading

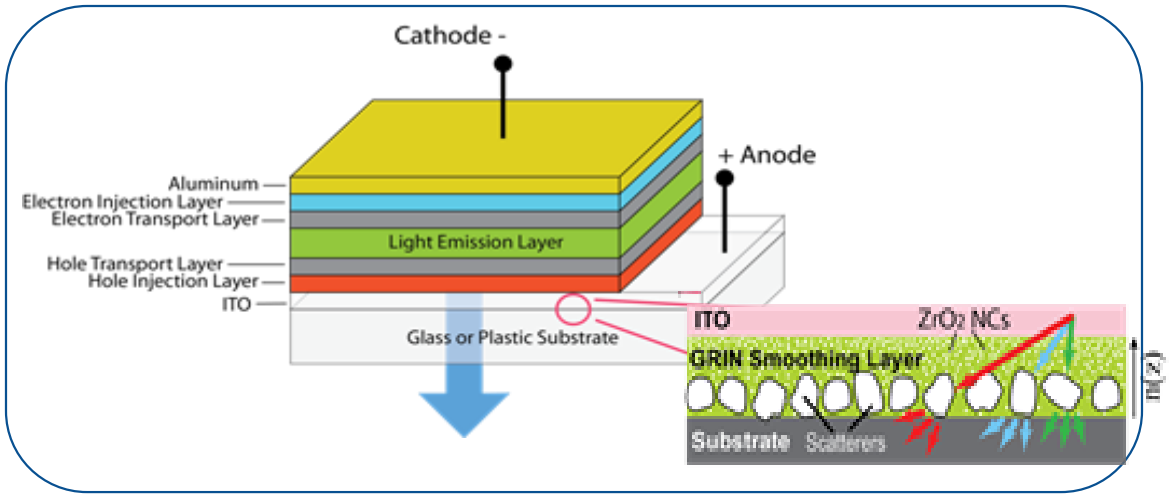
High Loading

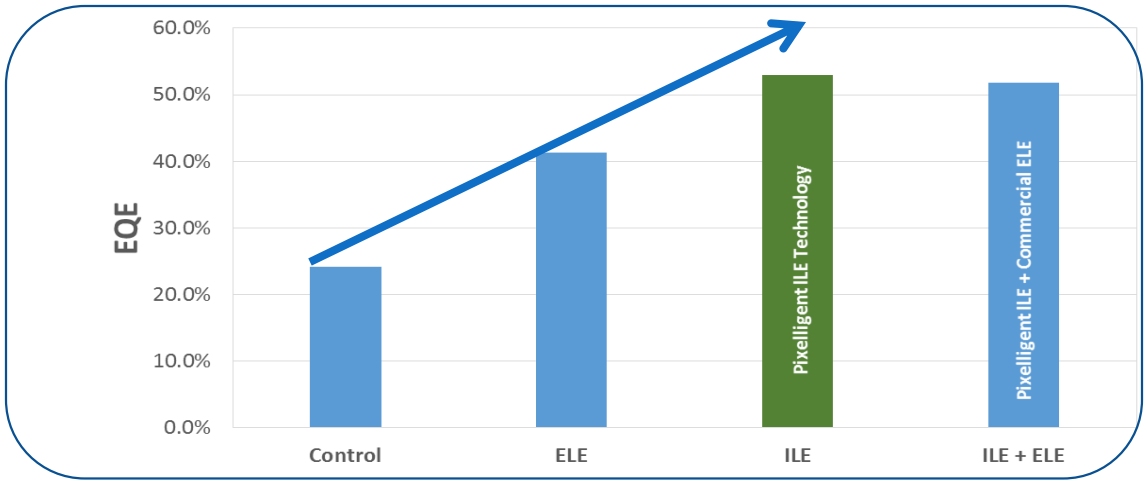
Loading	k	Haze
90 wt%	$<10^{-3}$	0.5%
80 wt%	$<10^{-3}$	0.5%
50 wt%	$<10^{-3}$	0.5%
0 wt%	$<10^{-3}$	0.4%

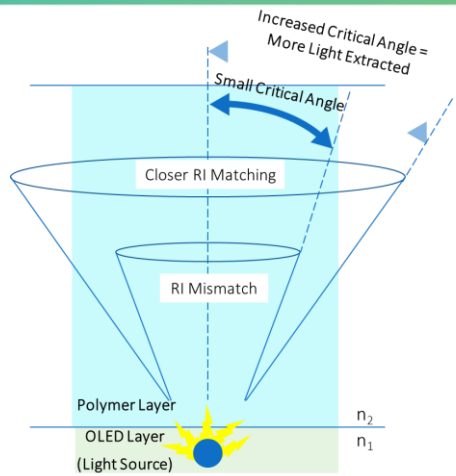


High %T and Low Haze at many NC loadings

PixClear OLED Lighting Application Doubles External Quantum Efficiency







Two High Refractive Index (HRI) Formulations:

- "HRI Transparent" with 1.78 RI
- "HRI with Scatterers" with 1.78 RI

"HRI Transparent" films provide:

- RI-matching (~1.8) to HRI layers within OLED structures, such as ITO
- Smoothing/planarizing layer

"HRI with Scatterers" films provide:

- Light extraction from HRI layers at flat interfaces

PixClear Display Applications

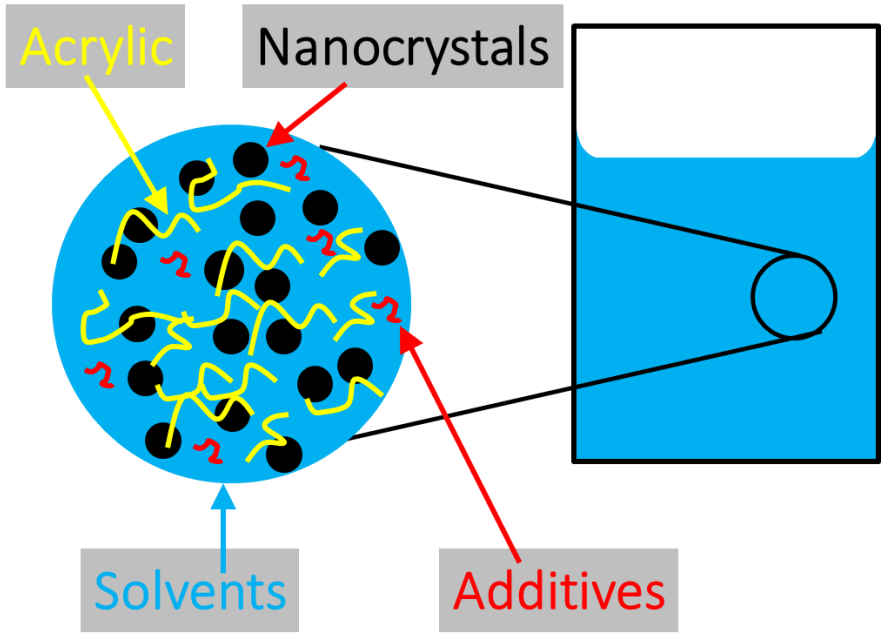
PixClear Delivers:

- ✓ 1.75+ RI
- ✓ 95% Transparency
- ✓ Flexible or Rigid
- ✓ 100%+ More Lumens
- ✓ Improved Scratch Resistance

Formulations & Inkjet Printing

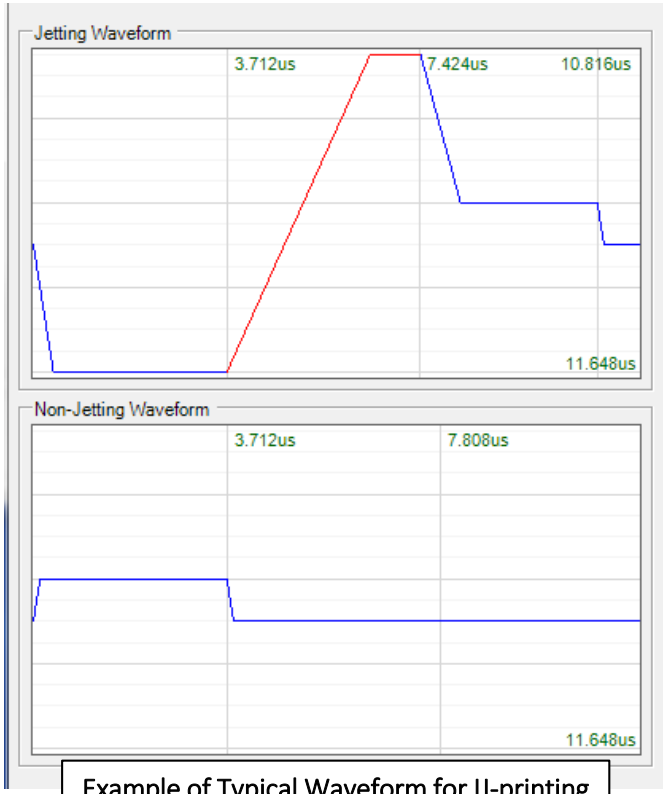
- "HRI Transparent" and "HRI with Scatterers" inks were deposited onto glass substrates to form:
  - Uniform film
  - Test patterns for OLED Lighting
- Data shown in presentation for proof-of-concept formulations

FujiFilm Dimatix DMP 2800



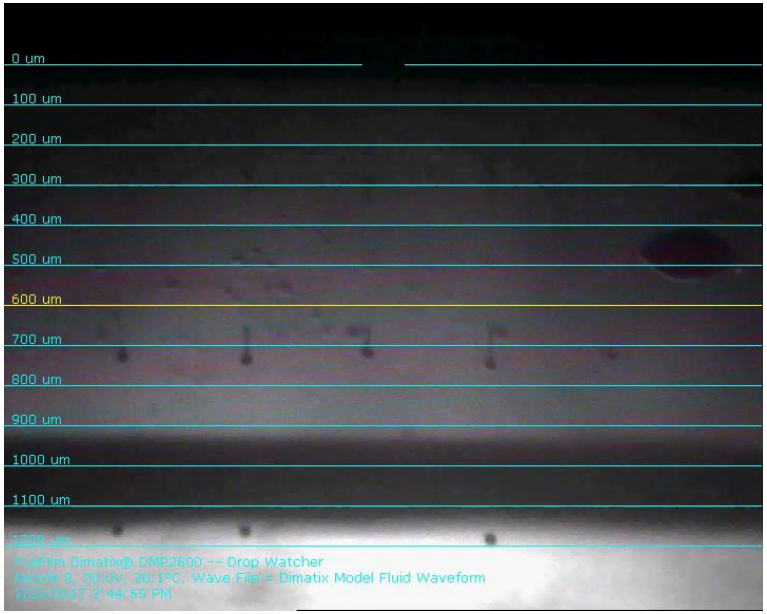
Inkjet Printing

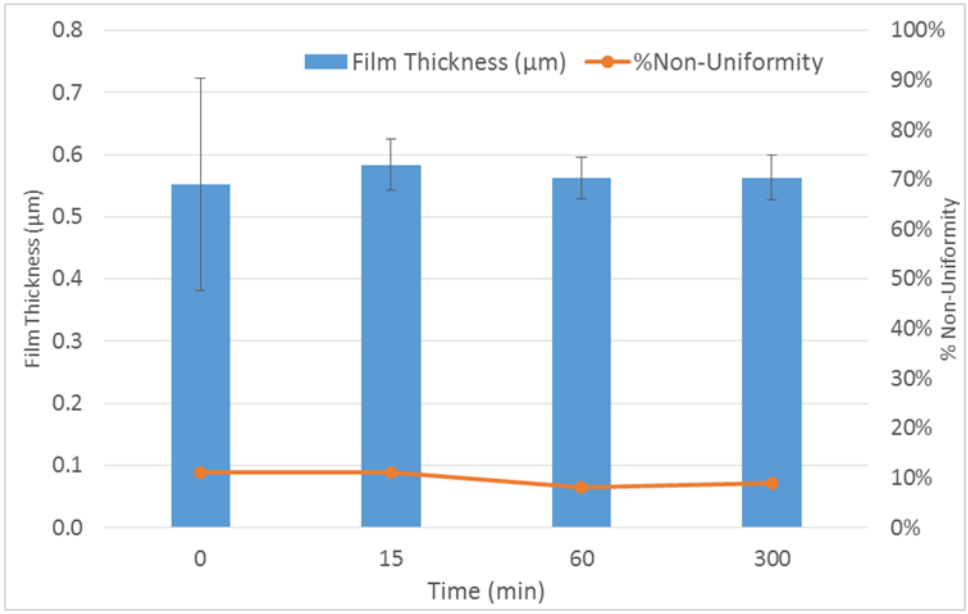
- IJ parameters adjusted to yield uniform films and patterns:
  - Jetting Frequency: 5 – 10 kHz
  - Applied Voltage: 15 – 30 V
  - Drop Spacing: 15 – 25 um
  - Heated Platen: 40 – 60 C
  - Waveform (right)
  - Slew Rate: 0.30 – 0.85
  - IJ cartridges (Nominal Drop Volume):
    - 1 pL (9-um nozzle)
    - 10 pL (20-um nozzle)



Example of Typical Waveform for IJ-printing

Jettability and Latency of “HRI Transparent” Inks

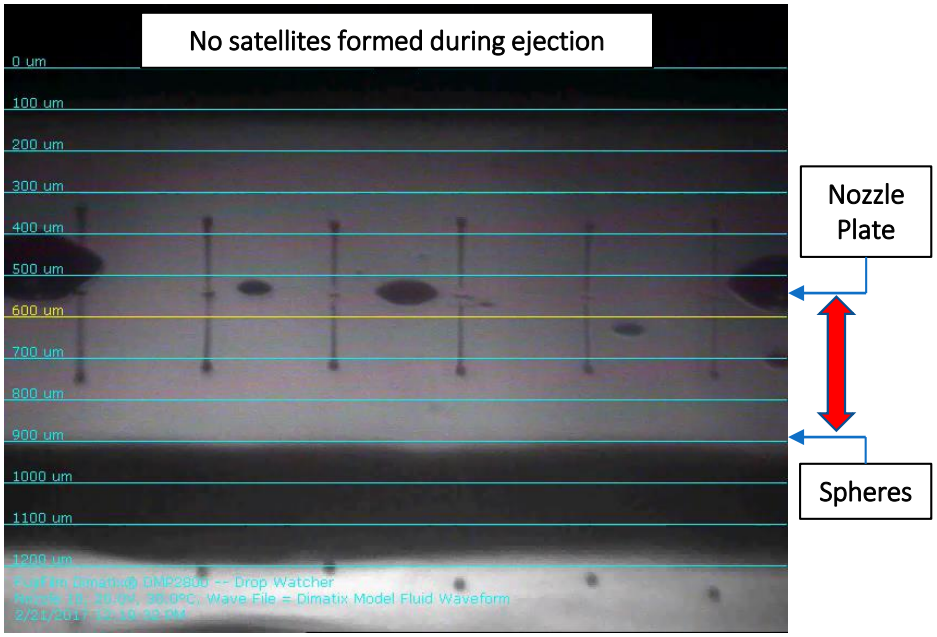




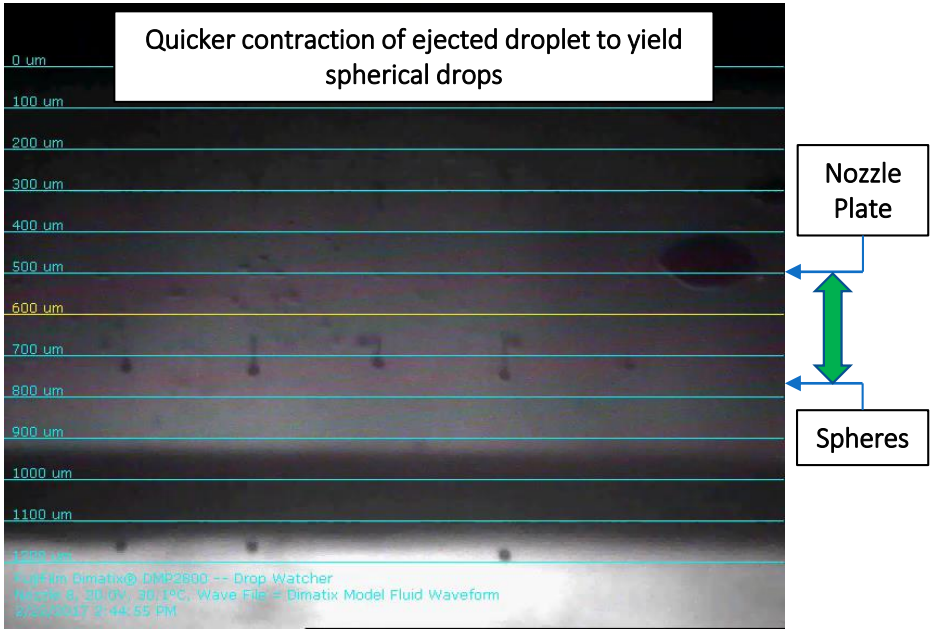
- “HRI Transparent” ink jetted forms spherical droplets with 1 pL cartridge under 5 kHz drive frequency
- Latency (reliability over time) was shown over a 300-min (5-hour) period at fixed IJ conditions
  - 15 V, 20 um drop spacing, 0.35 slew rate
- Film thickness and %Non-uniformity values were measured for films after each time interval
  - Films were UV-cured after printing

Controlled Jetting at Higher Drive Frequency

"HRI Transparent"

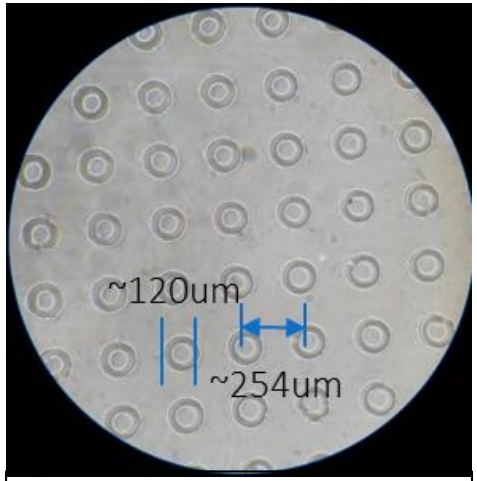


Modified "HRI Transparent"

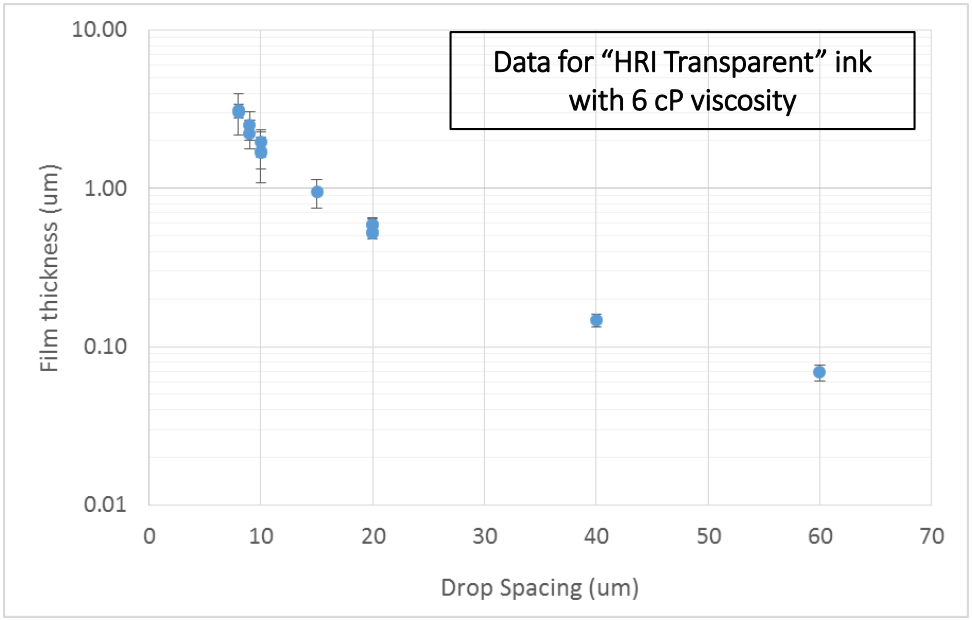


- ZrO_2 nanocomposite formulations can be easily re-formulated in order to achieve key performance targets
  - Improvements in surface tension, reduced wetting to nozzle plate, viscosity

Thickness Range for “HRI Transparent” Inks

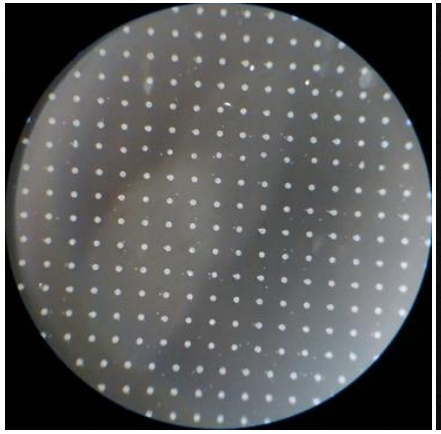


100x optical micrograph

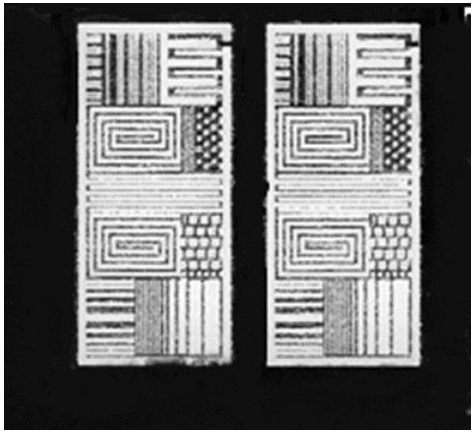


- 120-um diameter droplets have good size uniformity and wetting on glass substrates which allow uniform thin films to be printed
- A wide thickness range between 70 nm and 4 um was achieved for blanket films by modifying drop spacing
- 0.5 – 1.0 um films achieved good uniformity of ≤ 10%

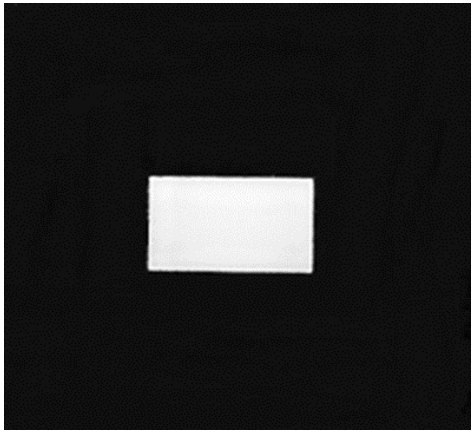
Patterning “HRI with Scatterers” Ink



254-um Drop Array



Dimatix Pattern

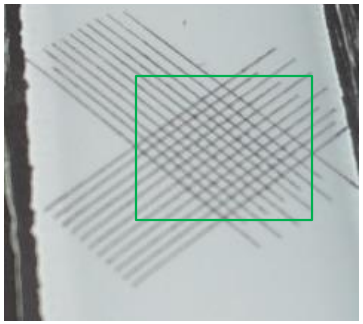


Device Pattern 1

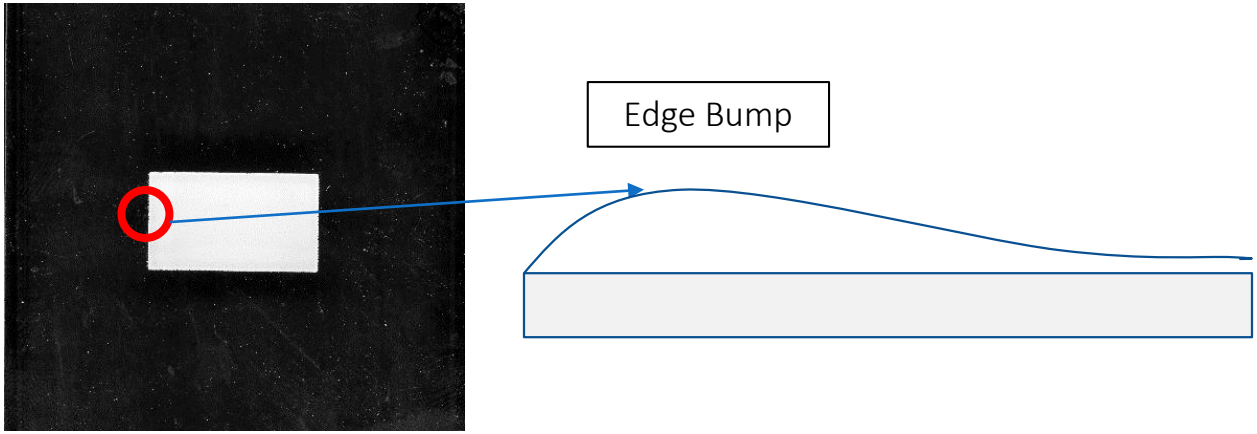
Device Pattern 2

- “HRI with Scatterers” formulation shows good-quality films, demonstrating how it can be IJ-printed to create complex dimensions and patterns
- Excellent film adhesion is also achieved for cured films via the crosshatch tape test

Cut regions maintain film integrity after tape removal

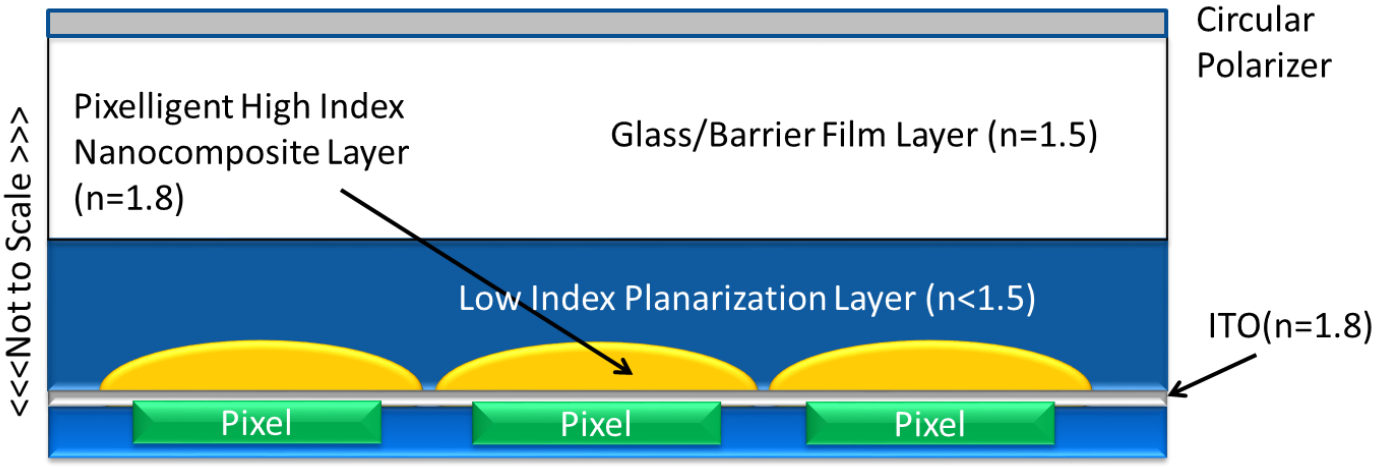


Print Quality



- Patterns with a resolution range from 847 – 1270 dpi (20 – 30 um drop spacings) have shown a smooth “edge bump” that ranges from 2 – 10 microns higher than the average film thickness
- Decreases in edge bump height can be achieved by increasing viscosity/solids loading and other additives to the formulation
- ITO deposition on top of the ILE layer and over the edge has been proven to be acceptable for OLED lighting device builds
  - ITO coating is continuous and smooth

OLED Lighting → OLED Display



- The HRI inks described in this presentation have been shown to improve OLED lighting performance
- Ongoing efforts are investigating similar HRI materials with capped ZrO2 formulations to enhance light extraction of OLED displays
- Under development:
  - Printing of HRI Lens → Lens are as small as OLED pixels
  - IJ-printing solvent-free formulations → removing solvent in the inks can prevent shrinkage of lenses and allow "snap-cure" after lens printing

Summary of ZrO_2 Nanocomposites

- Nanocomposite inks with UV-curable acrylics (and other monomers/polymers) and zirconia nanocrystals have good stability in formulation
  - Long pot life
  - Uniform film thickness
- PixClear capped ZrO_2 available with:
  - Different capping chemistries (polar/non-polar + functional/non-functional)
  - Compatibility in multiple solvents
- Films produced from ZrO_2 nanocomposite formulations have:
  - High transparency
  - High RI

Summary of Inkjet Printable Nanocomposites

- "HRI Transparent" and "HRI with Scatterer" inks can be formulated with various additives and solvents to tune surface tension and viscosity that are appropriate for inkjet printing
  - Viscosity tunable to be 2 – 30 cP
  - Surface tension adjustable to be ≥ 30 dyne/cm
  - Solvent additions to improve jetting and reduce nozzle wetting
- Multiple patterns can be printed using HRI inks with and without scatterer particles with good edge fidelity and adhesion to glass
- All of these attributes of our capped ZrO2 inks are ideal for improving light extraction in the OLED lighting and display devices

Acknowledgements

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Contact Us

Pixelligent Contact	Role	Email	Phone
Shree Deshpande	VP Business Development	sdeshpande@pixelligent.com	(1) 636-448-9484
Matthew Healy	VP Product Management	mhealy@pixelligent.com	(1) 443-529-8310 x38
Peter Guschl	Applications Engineering Lab Manager	pguschl@pixelligent.com	(1) 443-529-8310 x31

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