Printed Anodes and Internal Extraction Layers on Flexible Glass to Create Cost Effective High Efficacy Bendable OLED Lighting Panels

Jeff Spindler (PI), Ray Kesel, Michael Boroson, Marina Kondakova, Mike Andre, Tony Pleten, Tim Spencer

OLEDWorks LLC, 1645 Lyell Avenue Suite 140, Rochester NY 14606

PHASE I TECHNICAL OBJECTIVES

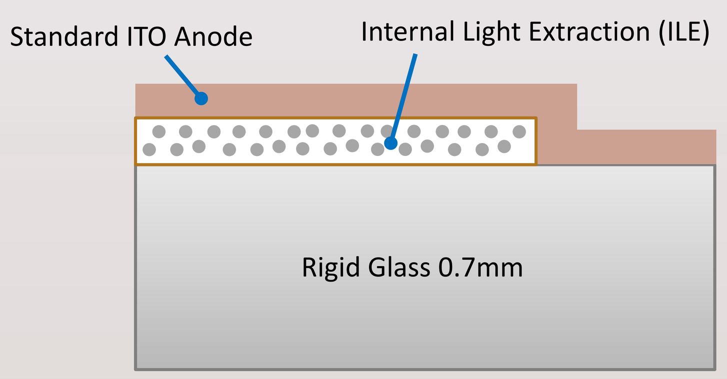
1. Demonstrate 90 lm/W white OLEDs with printable Internal Light Extraction (ILE) formulation and ITO anode
2. Demonstrate 90 lm/W white OLEDs with printable ILE and silver nanowire (AgNW) anode
3. Demonstrate high efficacy 100 lm/W bendable white OLED on thin glass with an optimized OLED architecture, printable ILE, and silver nanowire anode

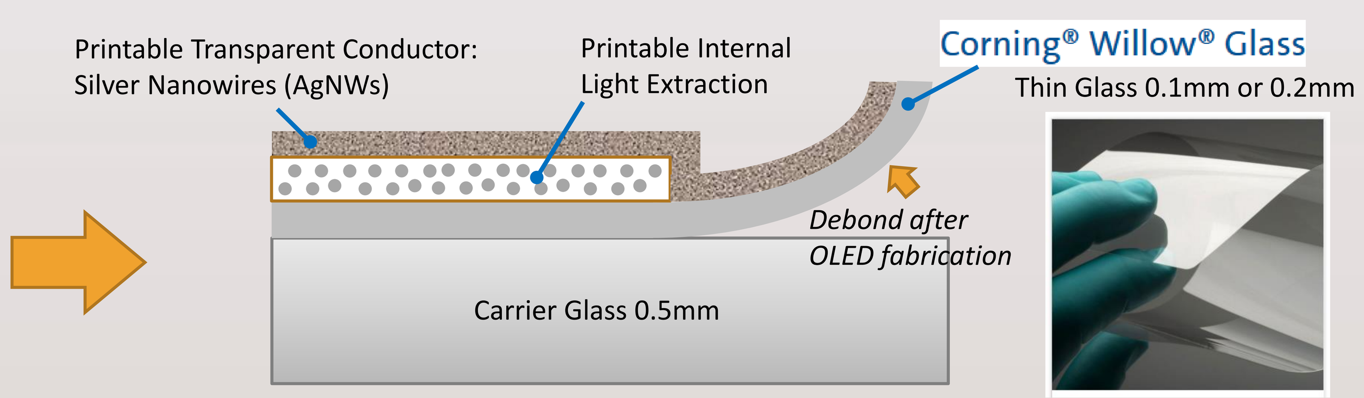
Current generation OLED lighting panels:

- Based on rigid glass – not compatible with R2R processing
- Inflexible ILE – not compatible with thin glass or plastic
- ITO anode – need large area sputtering equipment and photolithography patterning capability $$$

Future generation bendable OLED lighting panels:

- Based on ultrathin glass or plastic barrier films – compatible with R2R processing methods for lower cost
- Flexible low-cost ILE – compatible with thin glass or plastic
- Flexible low-cost anode such as AgNWs
- Possibility for full vertical integration and lower substrate cost



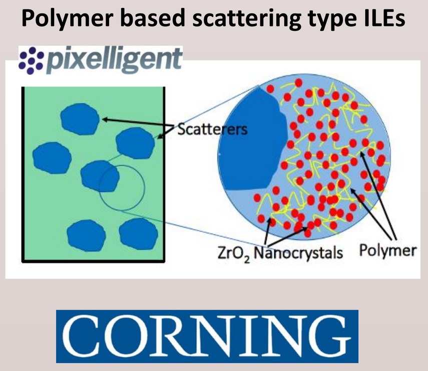


Printable/Flexible Internal Light Extraction:

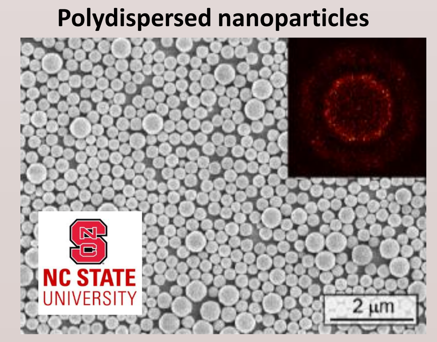
- Scattering type – TiO2 particles embedded in high refractive index (HRI) polymer
- Corrugated nanostructures – photonic crystals, polydispersed nanoparticles
- Sub-electrode microlens array (SEMLA)

All are potentially R2R compatible

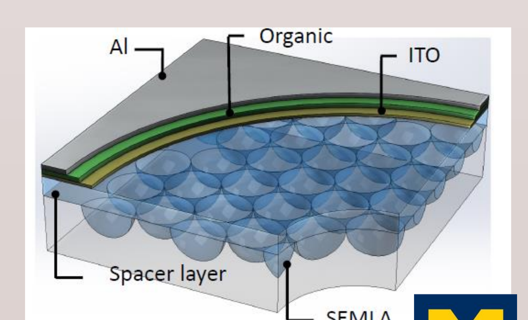
Polymer based scattering type ILEs



Polydispersed nanoparticles



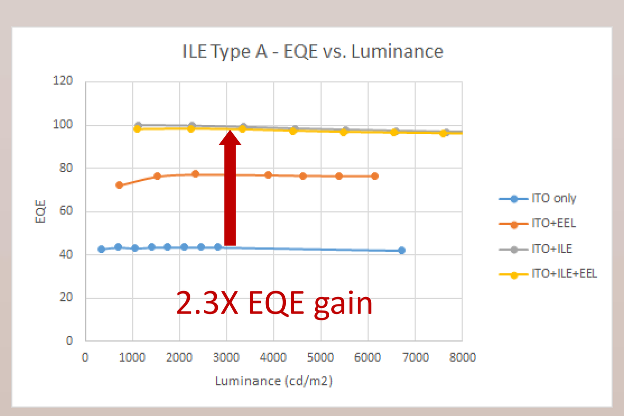
Profs. F. So, C.H. Chang, NC State U.

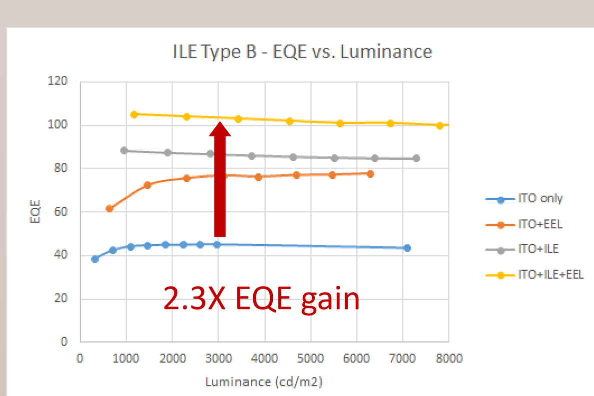


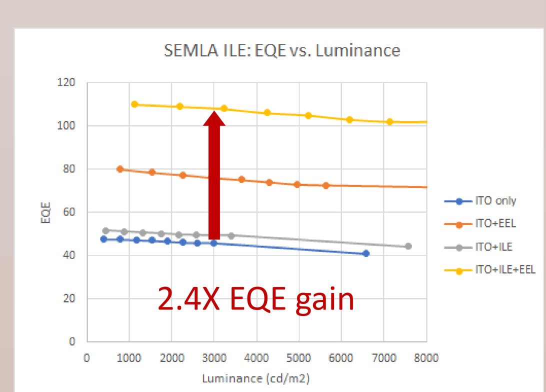
Sub-Electrode Micro Lens Array
Prof. S. Forrest, U. of Michigan

3-stack hybrid white OLED performance with various ILEs:

- Type A and B are scattering type
- Type A has higher haze (more scattering) than Type B ILE and does not benefit further from external extraction layer (EEL) to extract light waveguided in glass
- SEMLA ILE achieves highest EQE
- All ILEs can achieve 90 lm/W with 2.3-2.4X EQE gain vs. ITO-only control

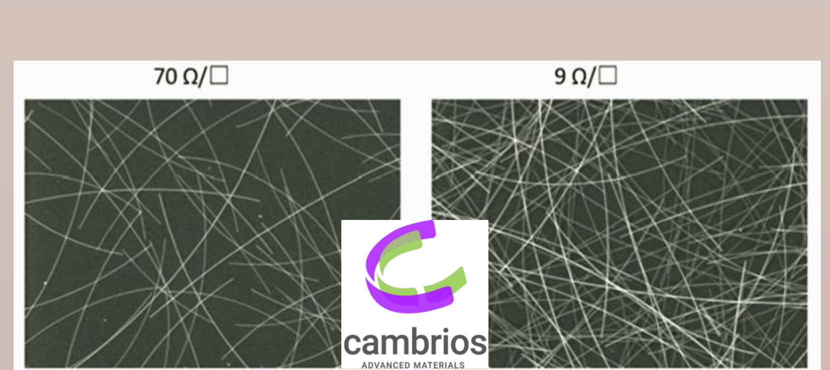






Flexible Silver Nanowire Anode:

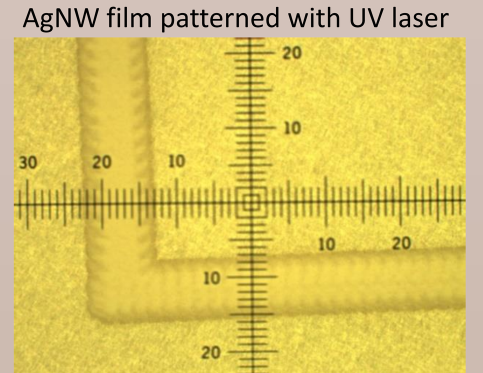
- Solution coated/printed – spin/slit/inkjet
- Laser patterned or direct patterned (inkjet)
- Large-scale use in commercial touch screen films; applied by R2R methods



Sheet resistance of AgNWs adjustable by varying film density:

- Spin coating – adjust spin speed or dilution
- Slit coating – adjust dilution of AgNW solution

AgNW film patterned with UV laser

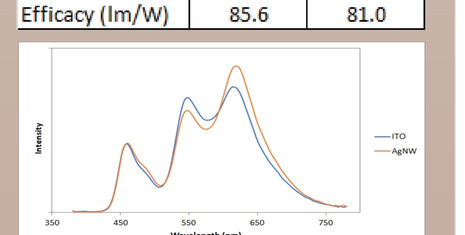


PHASE I CONCLUSIONS:

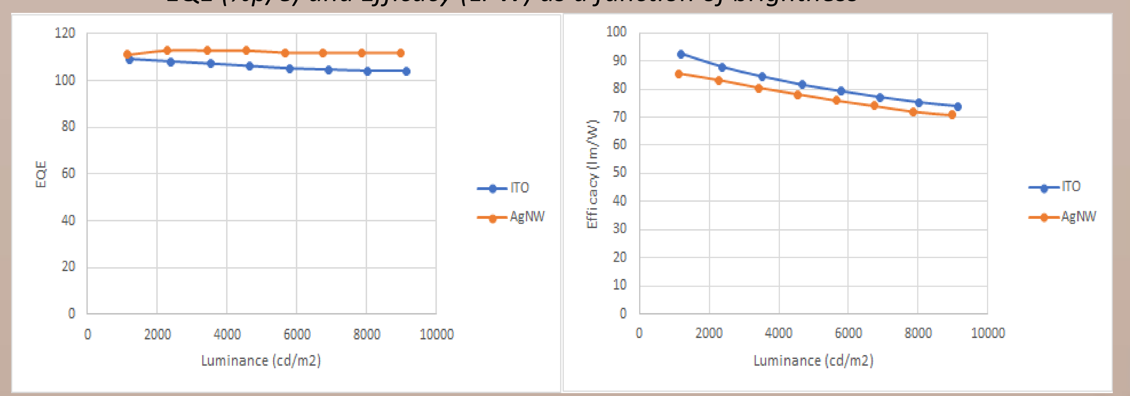
- Printable ILE can achieve 80-90 lm/W with both ITO and AgNW anodes combined with 3-stack hybrid white OLED
- AgNW anodes are compatible with thin glass substrates and future R2R processing

Performance at 3000 nits:

Metric	ITO	AgNW
Voltage (V)	8.7	8.8
Efficiency (cd/A)	236.0	227.0
EQE (%p/e)	107.0	113.0
Efficacy (lm/W)	85.6	81.0



EQE (%p/e) and Efficacy (LPW) as a function of brightness



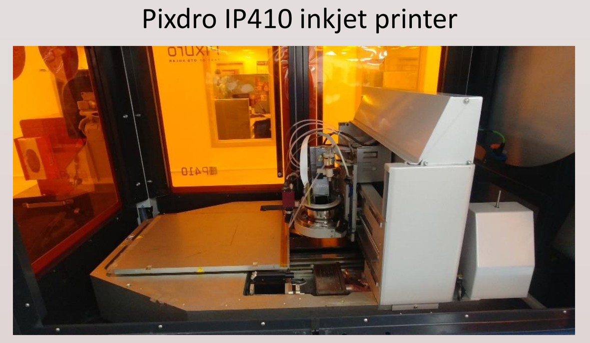
PHASE II GOALS:

1. Develop and scale the printable internal light extraction technology (ILE) on thin 0.25mm glass. Demonstrate baseline processes for depositing and patterning the ILE with ITO or AgNW electrodes on the unsupported thin glass. Evaluate, down select, and scale the most promising ILE technologies.
2. Demonstrate viability of the silver nanowire transparent conductive anode as a replacement for ITO anodes. This includes scaling the coating process to large area Gen2 glass substrates, demonstrating low cost patterning capability by direct patterning or laser patterning, and demonstrating long term reliability. Demonstrate large area transparent conductive films with at least 85% transmission in the visible region and less than 10 ohms/square sheet resistance.
3. Optimize the stacked white OLED architecture to achieve 120 lm/W at 3,000 cd/m^2 (standard brightness) and 100 lm/W at 8,000 cd/m^2 (high brightness) when combined with internal light extraction.
4. Develop and scale the technologies and methods to create robust flexible encapsulation and electrical interconnection for the large area bendable OLED lighting panel. Demonstrate capability to achieve the 100,000 hour lifetime target at standard brightness.
5. Increase the lumen output by combining above technology elements in a larger bendable OLED panel with area >150 cm^2 and capable of producing up to 600 lumens at high brightness.

Integration of Flexible ILE on thin glass (0.25mm)

- Potential for lower cost – no bonding/debonding process
- More robust than 0.1mm thin glass, trade-off in minimum bend radius
- Plan to scale inkjet-printable scattering ILE technology – now installing large area inkjet printer (Pixdro IP410)
- Continue to evaluate advanced ILE technologies

Pixdro IP410 inkjet printer



nTact slot die coater →

Flexible AgNW anode evaluation and scaling:

- Developing methods to locally pattern AgNW film within encapsulated OLED area to prevent side leakage of moisture
- Fabricate simple monochrome green OLEDs to test AgNW electrodes
- Plan to scale AgNW process – now installing large area slot-die coater with ability to pattern square or rectangular features

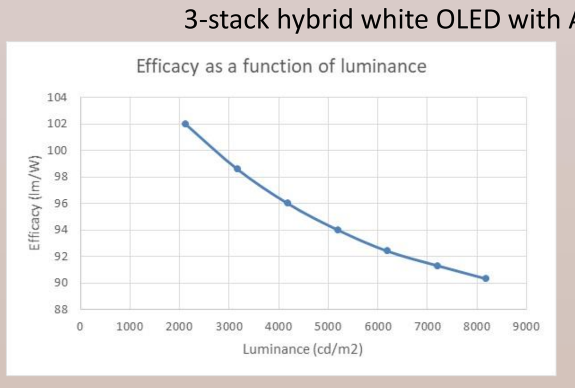
Green OLED with AgNW anode - Performance at 1 mA/cm^2

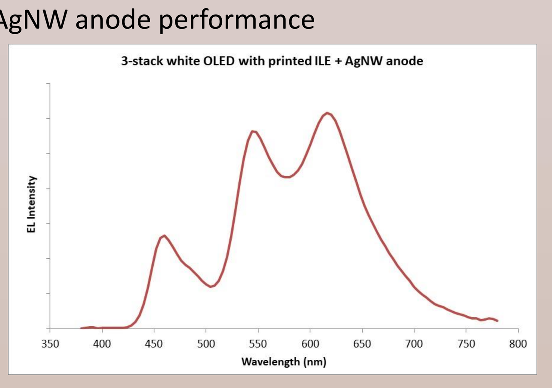
	No light extraction						With scattering external extraction film					
Device	V	cd/A	lm/W	CIEx	CIEy	EQE	V	cd/A	lm/W	CIEx	CIEy	EQE
4	2.7	107.4	124.8	0.41	0.58	30.4	3.0	143.8	148.2	0.43	0.55	42.5
5	2.6	110.5	132.7	0.41	0.58	31.4	2.8	144.5	159.7	0.43	0.55	42.7
7	2.7	87.6	101.8	0.41	0.58	25.4	3.1	126.6	130.2	0.43	0.55	37.4
8	2.7	101.3	119.9	0.41	0.58	29.5	2.9	145.3	156.7	0.44	0.55	42.9
9	2.5	92.8	115.0	0.41	0.57	27.2	2.9	135.4	147.3	0.44	0.55	40.1
Avg	***2.6***	***99.9***	***118.8***	***0.41***	***0.58***	***28.8***	***2.9***	***139.1***	***148.4***	***0.43***	***0.55***	***41.1***

Develop higher efficiency stacked white OLED architecture

- Investigate phosphorescent (PH) and TADF blue emitters and all-phosphorescent white stacks
- Develop all-phosphorescent multi-stack white structures
- Continue to improve performance of hybrid white multi-stack structures using FL blue and PH red and green emitters; early results achieving nearly 100 lm/W at 3000 nits

3-stack hybrid white OLED with AgNW anode performance





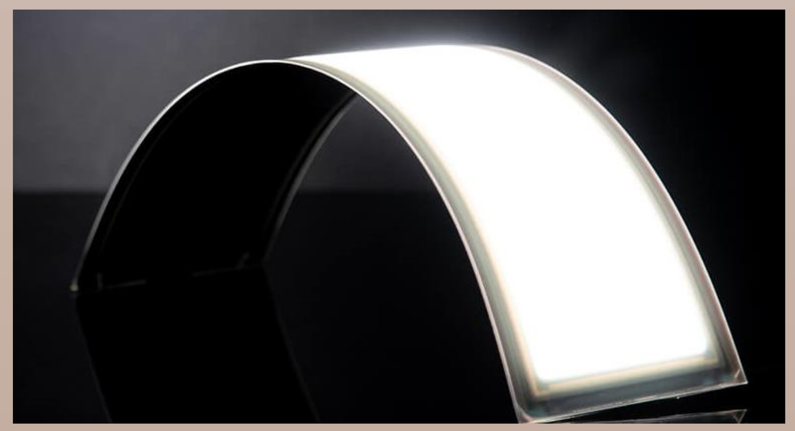
Large area bendable OLED lighting panel integration

- Developing technologies for flexible encapsulation and robust electrical connection
- Developing large area rectangular OLED panel with > 200 cm^2 lit area to produce 600 lumens
- Integrate all component technologies on large area bendable OLED lighting panel with printed ILE and AgNW anodes to achieve at least 100 lm/W and 100,000h lifetime

OLEDWorks' Brite3 LumiCurve Wave: The World's First High Brightness OLED Lighting Panel based on Ultrathin Glass

CURRENT Performance (Brite3):

- Efficacy up to 62 lm/W
- Produces up to 300 lumens
- Lifetime: 30,000 hours
- No Internal Light Extraction



FUTURE Performance (Brite4):

- Efficacy: 100+ lm/W
- Flux: 300+ lumens
- Lifetime: 100,000 hours

Need high performance flexible ILE!