

# Silver Nanowire Electrodes: Enabling Flexible, Transparent and Cost Effective OLED Lighting

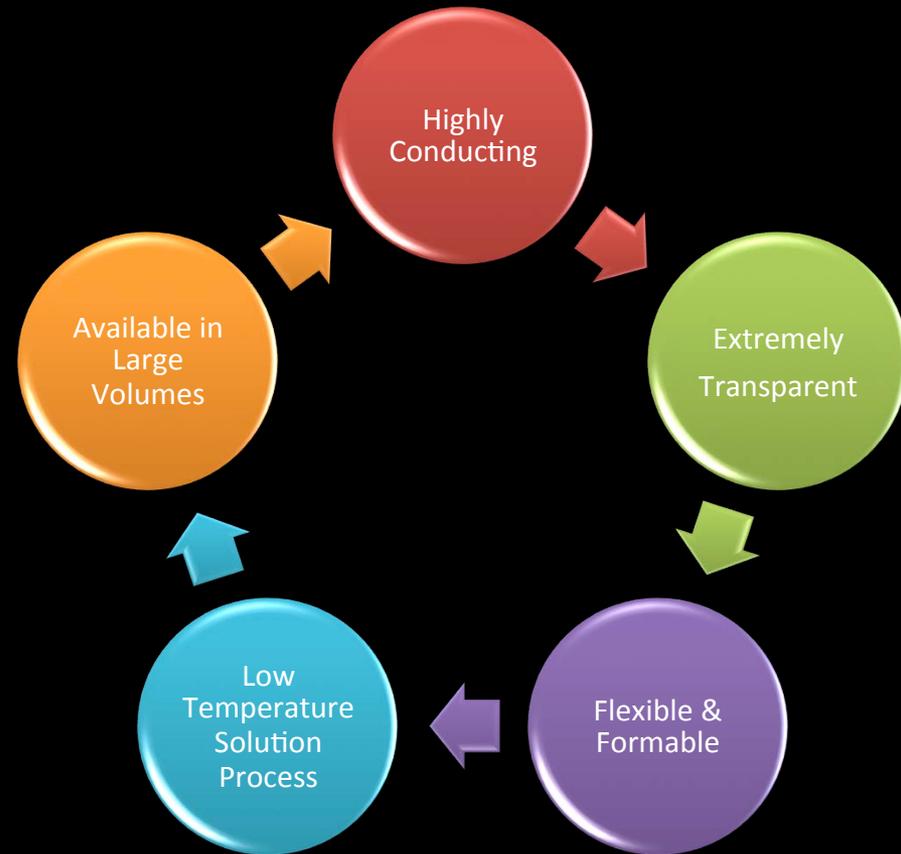
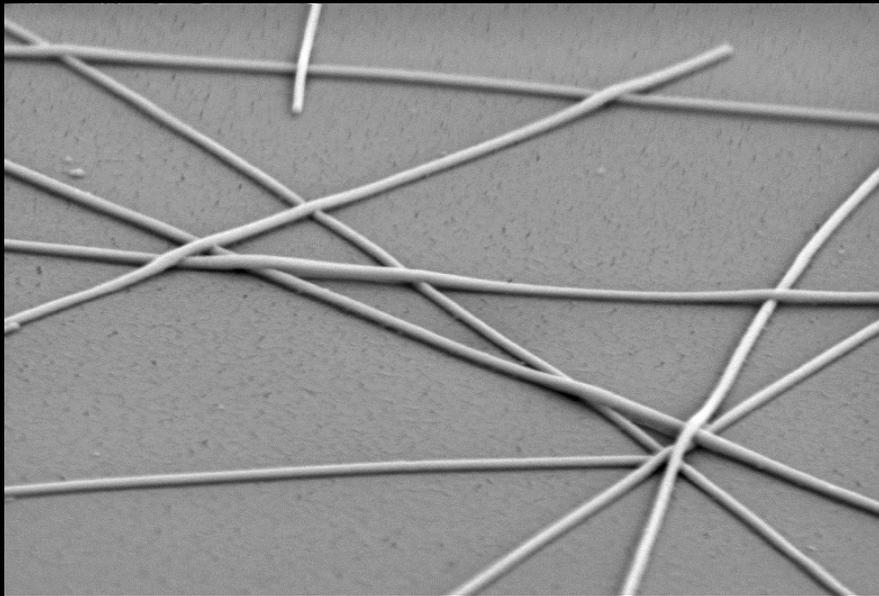


DOE SSL R&D Workshop  
January 27, 2015

Rahul Gupta  
Senior Director, Business Development  
rgupta@Cambrios.com



# Cambrios ClearOhm<sup>®</sup> Transparent Conductor: Single Crystal Silver Nanowire



# Numerous ClearOhm<sup>®</sup> Touch Sensor Products In The Market

## Monitors and All-In-One PC's



LG ET83  
23"  
Monitor



Lenovo A740  
27" AIO



HP 23" AIO



LG ET63  
23" Monitor



Lenovo A540  
23" AIO



Fuhu Nabi  
24" Bigtab



LG V325  
23" AIO



Lenovo Flex 20  
20" AIO



Fuhu Nabi  
20" Bigtab

## Smartphones



**BenQ**  
BenQ F5



**Karbonn**  
Karbonn  
A29 (India)



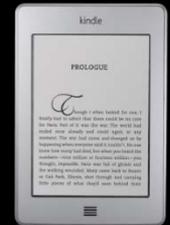
Advan S5G  
5" and 5.7"



Medias X on  
NTT docomo



## Tablets & eReaders



## POS Monitors



**GVISION**

15" POS  
Monitor

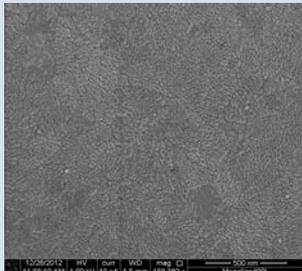
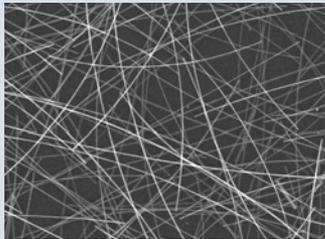
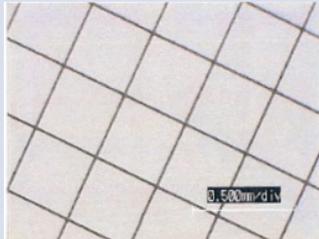
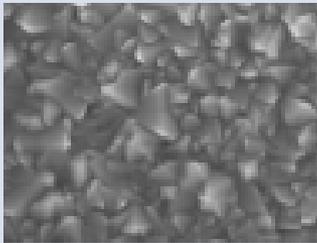
# Robust Supply Chain In Place



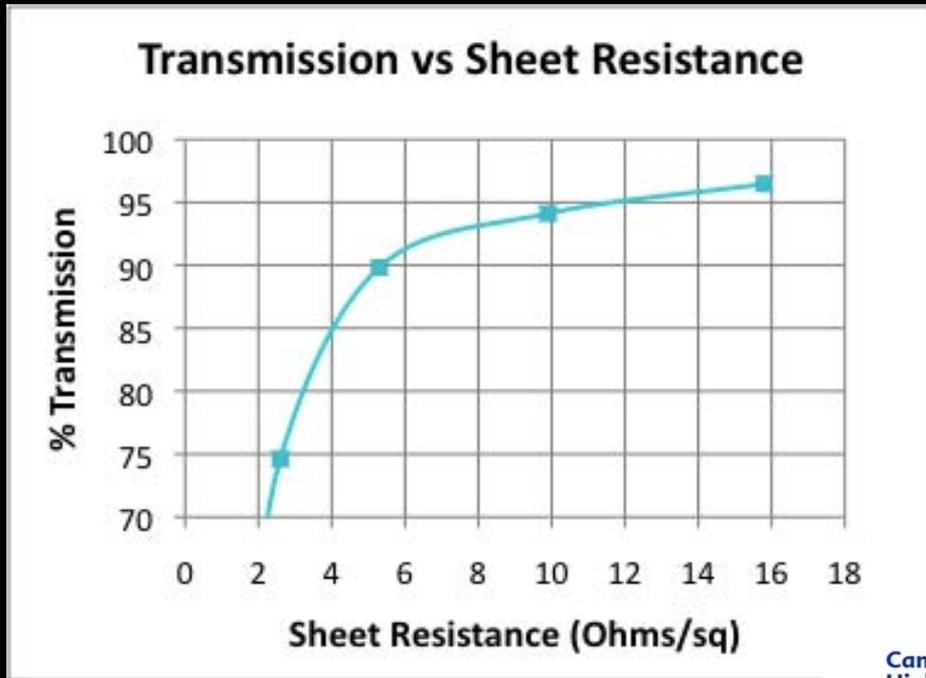
# Transparent Conductor Requirements For OLED Lighting

- Performance
  - Current spreading to ensure large area with uniform emission, flexible, transparent
  - Efficiency and Lifetime
  - Compatible with light extraction or improves light extraction
- Manufacturability
  - Processable
  - Scalability of process
- Cost structure to enable cost effective OLED lighting

# Options For Transparent Electrodes

|            | ITO                                                                                                                                                                               | NW                                                                                                                                 | Metal Grid                                                                                                                                                                                                          | FTO/AZO                                                                                                                                                                                                                               |
|------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|            |                                                                                                  |                                                  |                                                                                                                                  |                                                                                                                                                    |
| Pros       | <ul style="list-style-type: none"> <li>Well established incumbent</li> </ul>                                                                                                      | <ul style="list-style-type: none"> <li>Low cost solution process</li> <li>Low capex</li> <li>Scalable</li> <li>Flexible</li> </ul> | <ul style="list-style-type: none"> <li>High conductivity (&lt;1-50 ohms/sq)</li> <li>Flexible</li> </ul>                                                                                                            | <ul style="list-style-type: none"> <li>10-20 ohms/sq</li> <li>Compatible with glass production</li> </ul>                                                                                                                             |
| Challenges | <ul style="list-style-type: none"> <li>Limited conductivity, especially on plastic</li> <li>Brittle/not flexible</li> <li>High CapEx</li> <li>Expensive vacuum process</li> </ul> | <ul style="list-style-type: none"> <li>5 ohms/sq with &gt;90% transmission</li> </ul>                                              | <ul style="list-style-type: none"> <li>Optically visible</li> <li>Large openings → charge spreading</li> <li>High thickness → needs dielectric/planarization</li> <li>Lifetime issues: needs passivation</li> </ul> | <ul style="list-style-type: none"> <li>Cost competitive only at very high volumes (inline with float glass process)</li> <li>Brittle/not flexible</li> <li>Roughness</li> <li>High CapEx</li> <li>Expensive vacuum process</li> </ul> |

# Low Sheet Resistance With High Transmission: Enables Metal Grid Free Large OLED Tiles



**Cambrios Partners with Novaled to Produce 100 sqcm OLED Lighting Tile with New Highly Transparent Electrodes**



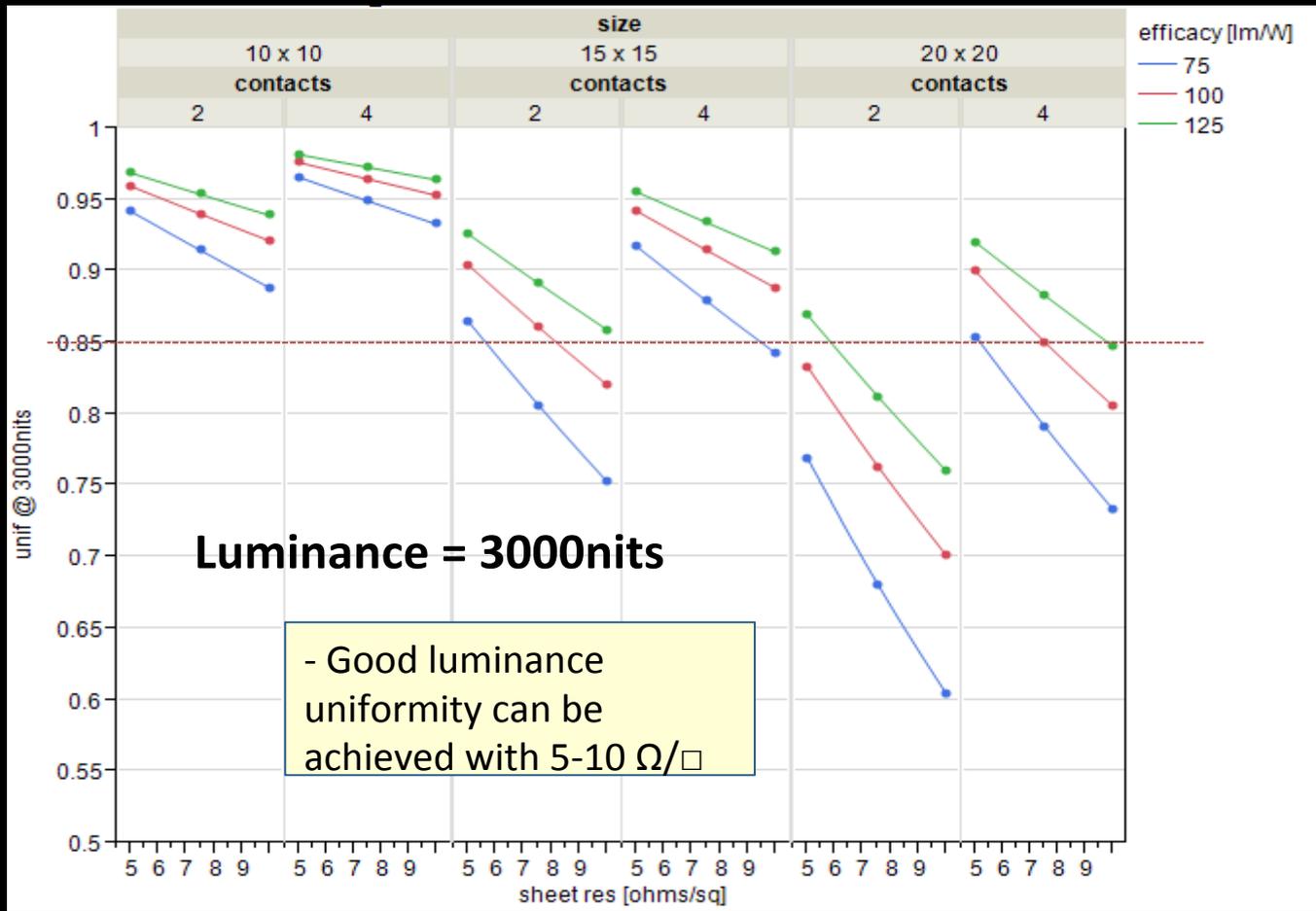
*Partnership Enables Innovative OLED Tile Design and Shapes the Future of OLED Lighting Technology*

SUNNYVALE, Calif., DRESDEN, Germany, April 15, 2013 – Cambrios Technologies Corporation, the leader in nanotechnology-based solutions for the transparent and flexible conductor markets, and Novaled, a leader in the research, development and commercialization of technologies and materials that enhance the performance of OLEDs (Organic Light Emitting Diode) and Organic Solar Cells, announced today the successful creation of a metal grid free large area 100 cm<sup>2</sup> (10 cm by 10 cm) OLED lighting tile, using Cambrios ClearOhm™

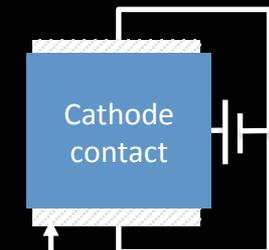
# Luminance Uniformity : Enabling 20cm x20 cm Tiles Without Metal Grids

Variables: Efficiency, Sheet resistance, 2 vs 4 sided contact

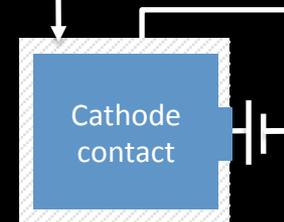
$$Uniformity = 1 - \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$



2 sided anode contact

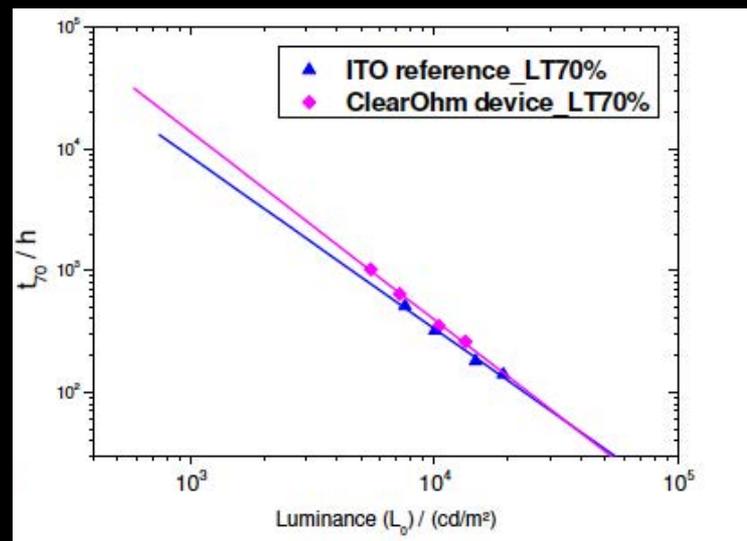
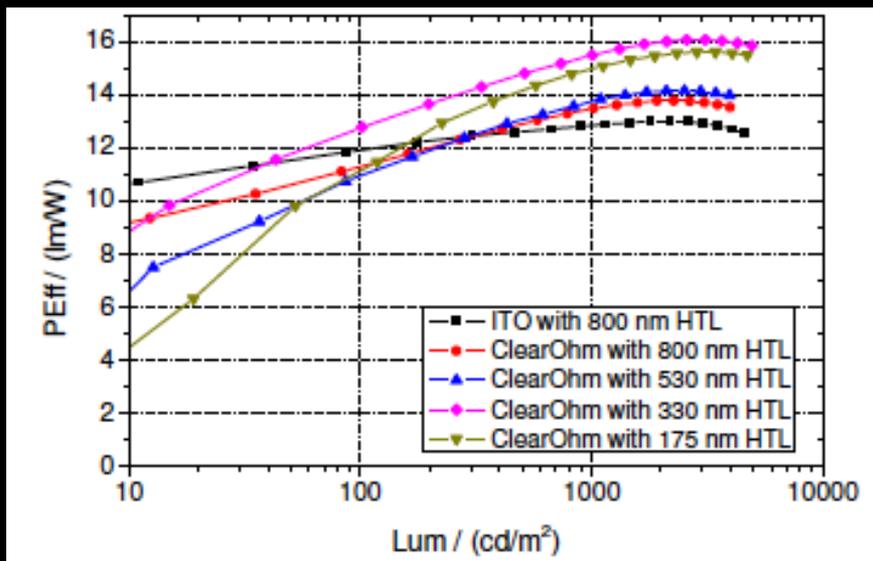


Anode contact



4 sided anode contact

# Similar Efficiency and Lifetime as ITO



| Sample               | ClearOhm device |      |      |     | ITO reference   |     |     |     |
|----------------------|-----------------|------|------|-----|-----------------|-----|-----|-----|
|                      | D1              | D2   | D3   | D4  | D1              | D2  | D3  | D4  |
| Diode #              | D1              | D2   | D3   | D4  | D1              | D2  | D3  | D4  |
| Curr. dens. (mA/cm²) | 30              | 40   | 60   | 80  | 30              | 40  | 60  | 80  |
| 50% lifetime (h)     | 2425            | 1660 | 1000 | 770 | 1350            | 940 | 560 | 410 |
| 70% lifetime (h)     | 1020            | 640  | 350  | 260 | 510             | 320 | 180 | 140 |
| LT50 at 1000 cd/m²   | 21400, [n=1.29] |      |      |     | 18500, [n=1.30] |     |     |     |
| LT70 at 1000 cd/m²   | 14100, [n=1.55] |      |      |     | 9500, [n=1.46]  |     |     |     |

# CAPACITY, SCALABILITY AND COST

# Cambrios Has Capacity To Meet Growing Demand



2013

22,000 L/year



2014

175,000 L/year

# Low Cost Solution Process: Roll-To-Roll Or Sheet Glass Or Plastic Substrates



Cambrios 300mm pilot coater; ~\$300k



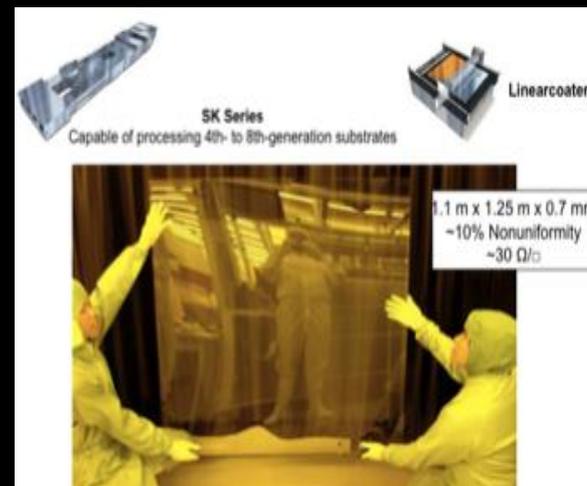
Low Cost  
Pilot



Low Cost  
Production



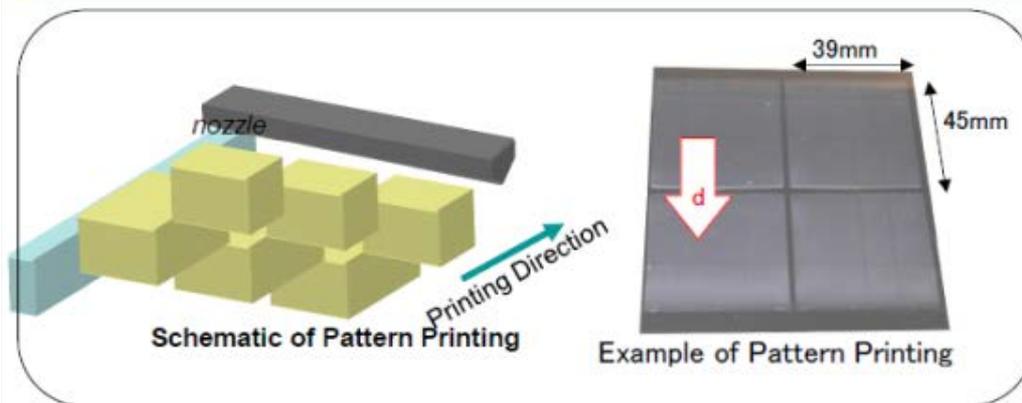
R2R production coater: 3-6 Million m<sup>2</sup>/year capacity  
Investment \$~2 Million



Production sheet slit coater (G4.5)  
0.5-1 Million m<sup>2</sup>/year capacity  
Investment \$~1.5 Million

# Printed Silver Nanowire Electrodes Eliminate Cost Of Patterning

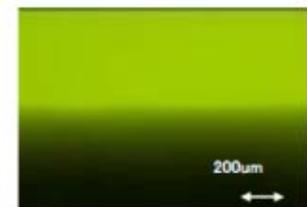
Accurate Direct Patterning Printing Process Has Been Achieved by Controlling surface morphology, Ink Viscosity, Surface Tension, Drying Condition



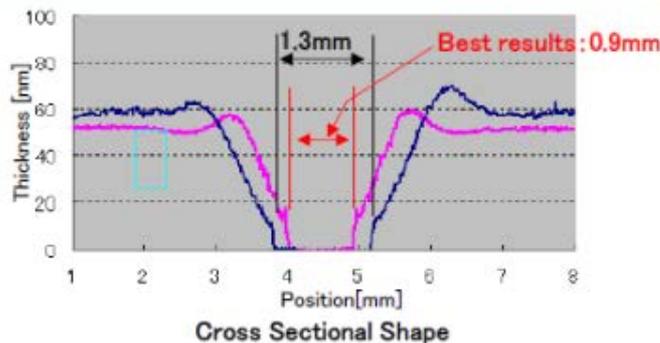
Very Similar shape of Wet Etched ITO

Ref: ITO Pattern Edge

Direct Patterned Edge

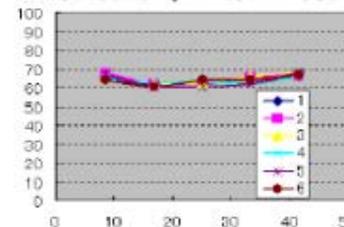


Sub mm Order Pattern Gap

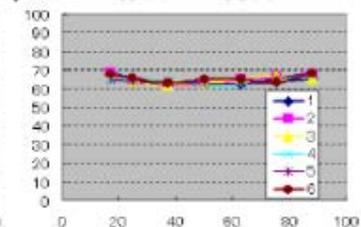


Less than  $\pm 10\%$  Accuracy of the Thickness

Distribution (Printed Direction)



Width Direction

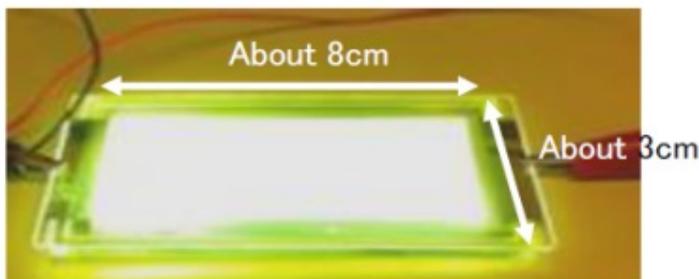


Courtesy of Tazumo

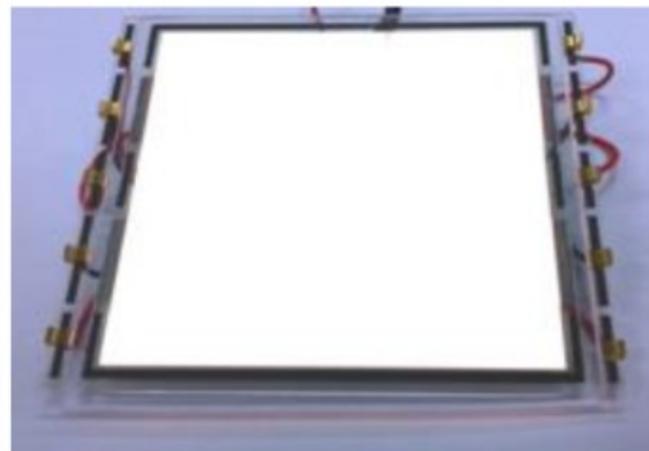
# Large Area OLED Tiles With Printed Silver Nanowire Electrodes

Newly developed printed transparent electrode can replace ITO

OLED Lighting Panel replace with Printed Electrode (25 cm<sup>2</sup>)



|                   | Sheet Resistance ( $\Omega/\square$ ) | Intensity (cd/m <sup>2</sup> ) | Voltage (V)           | E.Q.E. (vs ITO) | Emission area (cm <sup>2</sup> ) |
|-------------------|---------------------------------------|--------------------------------|-----------------------|-----------------|----------------------------------|
| ITO               | 10                                    | ref                            | ref                   | ref             | 25                               |
| Printed Electrode | 10                                    | <math>\pm 2\%</math>           | <math>\pm 0.1V</math> | Same as ref     | 25                               |



White OLED Panel with Printed Electrode (64 cm<sup>2</sup>)

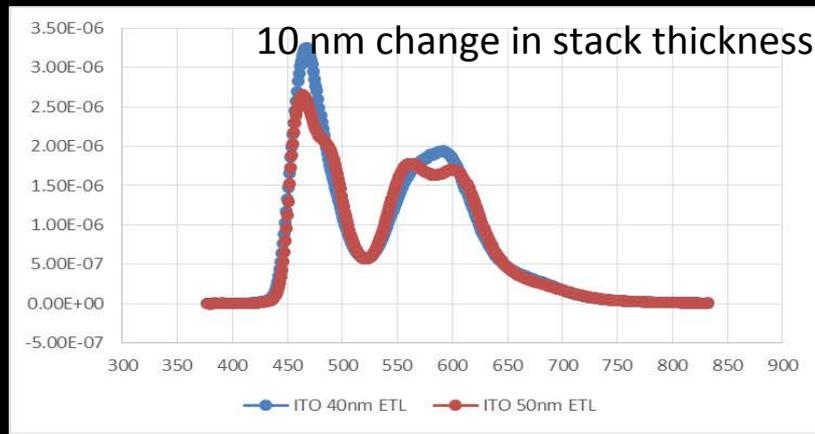
# Cost Savings by using ClearOhm<sup>®</sup> Electrodes for OLED/PV

- Solution process for coating vs vacuum process for ITO: Depreciation <\$0.1-0.6/m<sup>2</sup> vs ~\$9/m<sup>2</sup>
- Printing to eliminate expensive photo patterning
  - Photo-patterning costs ~15-20/m<sup>2</sup> at G4.5
  - Or use low cost laser patterning or screen printable etchants
- Metal Grid Free OLED Lighting Tiles
  - Eliminates metal grid
  - Eliminates bank structures/passivation layers

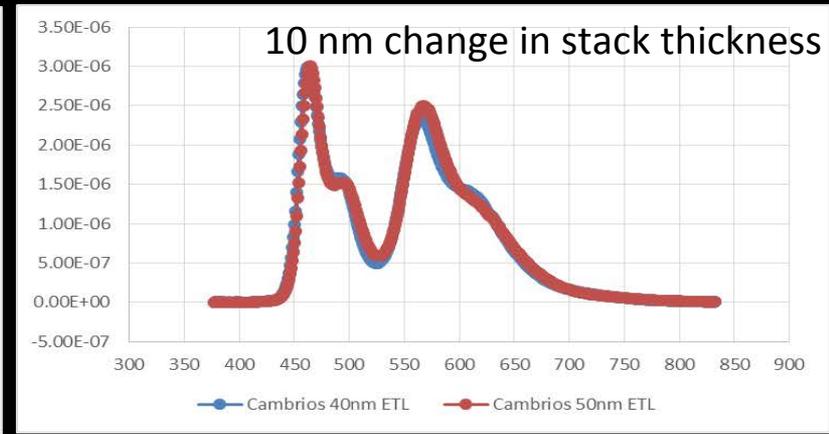
# Improved Process Window For Higher Yields Scalability to Gen 5/8 Sheets or R2R

~3% Change in stack thickness

Large change in color with ITO Anode



No change in color with ClearOhm Anode



- No coherent reflection from Nanowires → no micro-cavity effect
- Color does not change with thickness of stack
  - Wider process Window even for Gen 5
  - No need to bin products based on location on substrate

# Integrated Substrates With Nanowires

- Low temperature process for nanowires
- Opens up choices for low cost planarization layers on top of scattering/high index layers
- Can combine scattering/high index materials with nanowires

Controlled by  
OLED Maker

Controlled by  
Substrate maker

Top encapsulation

Cathode

ETL

EML

HTL

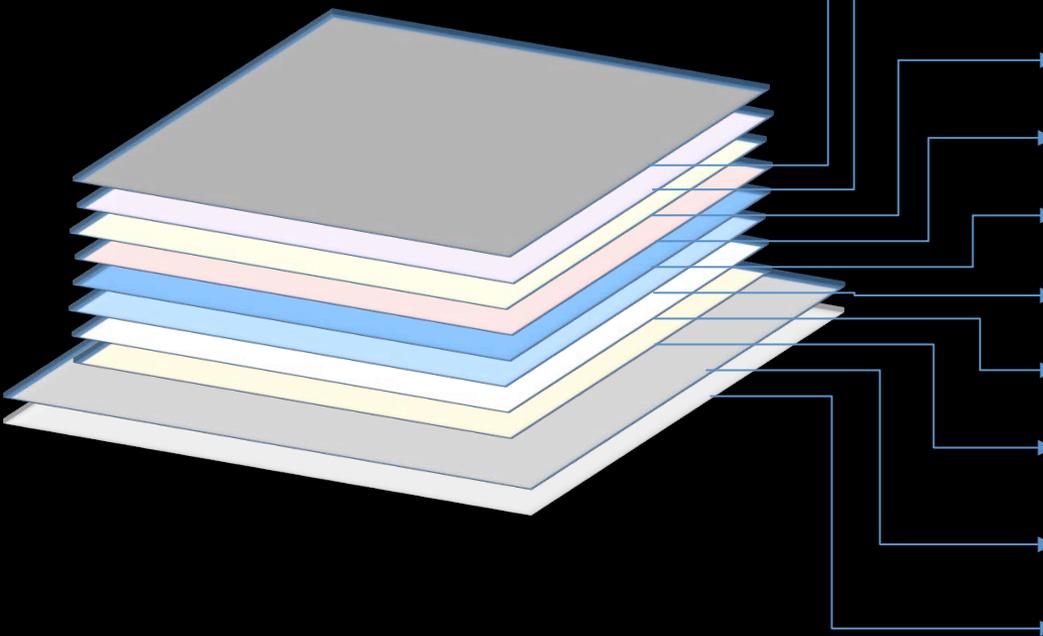
HIL

Anode

Index/scattering/planarizing layers

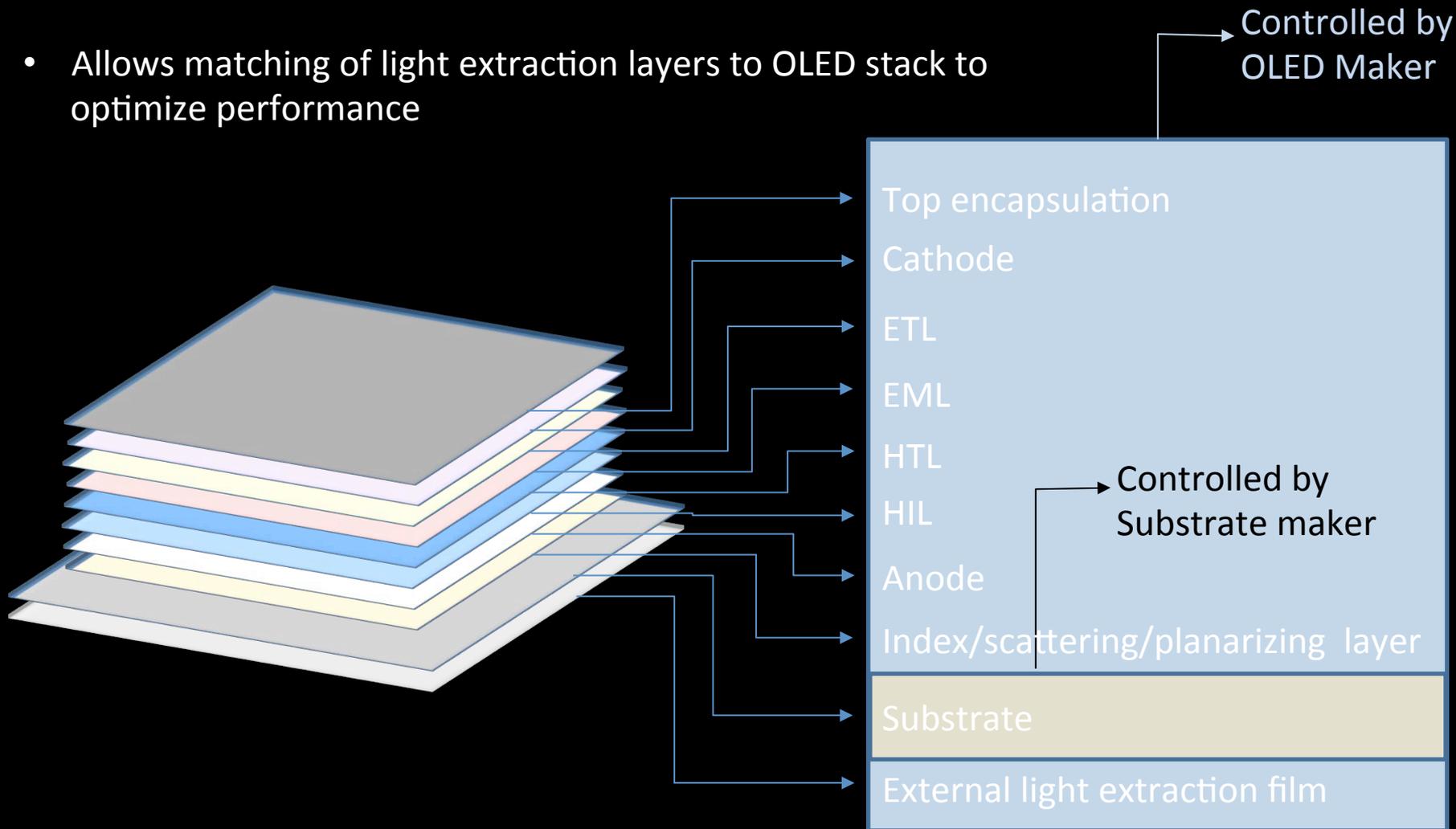
Substrate

External light extraction film



# Silver Nanowires Allow OLED Makers To Optimize Internal Light Extraction

- Allows matching of light extraction layers to OLED stack to optimize performance



## Automobiles



## Walls/Glass/Buildings



## Clothes

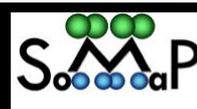
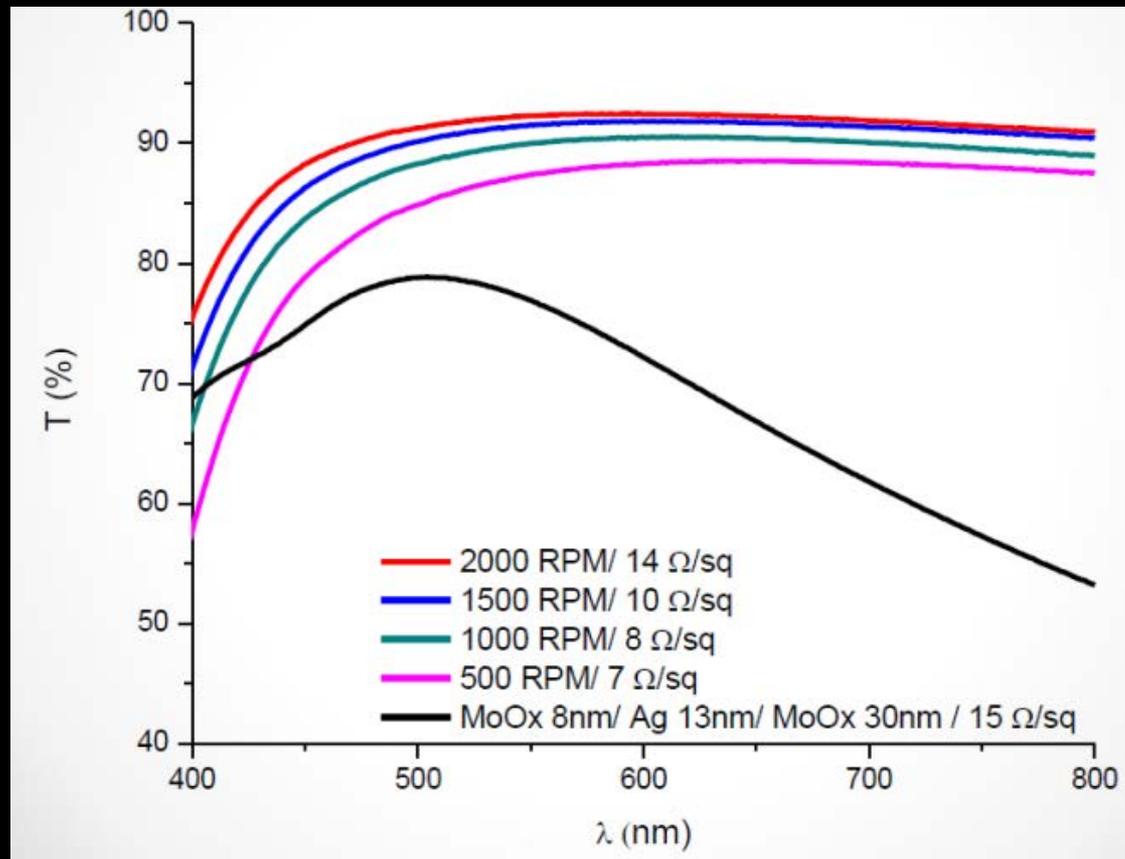


## Furniture



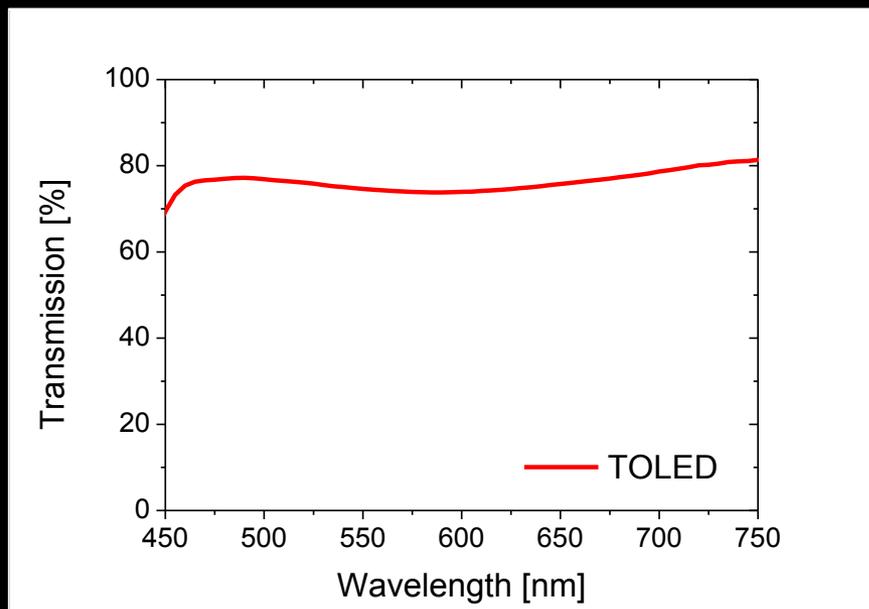
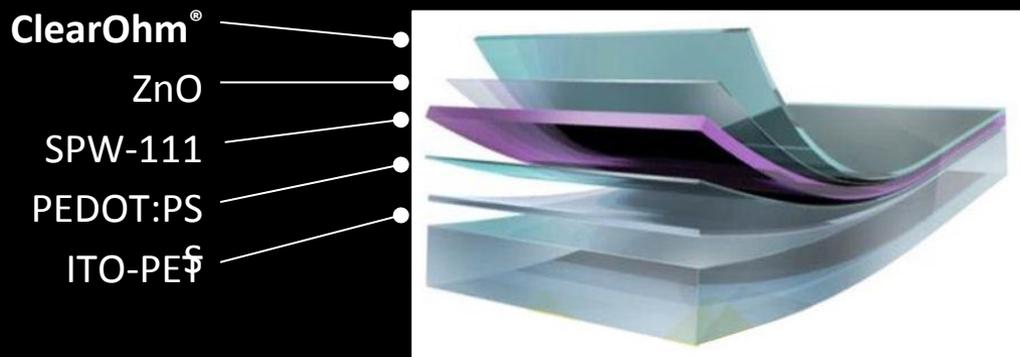
# ENABLING TRANSPARENT FLEXIBLE & FORMABLE PRODUCTS

# ClearOhm<sup>®</sup> Material: Excellent Performance As Top Transparent Electrode



Acknowledgements: Matthew White, Markus Scharber, Lucia Leonat, Michael Drack, Martin Kaltenbrunner, Siegfried Bauer, and Serdar Sariciftci

# Fully printed Transparent OLED



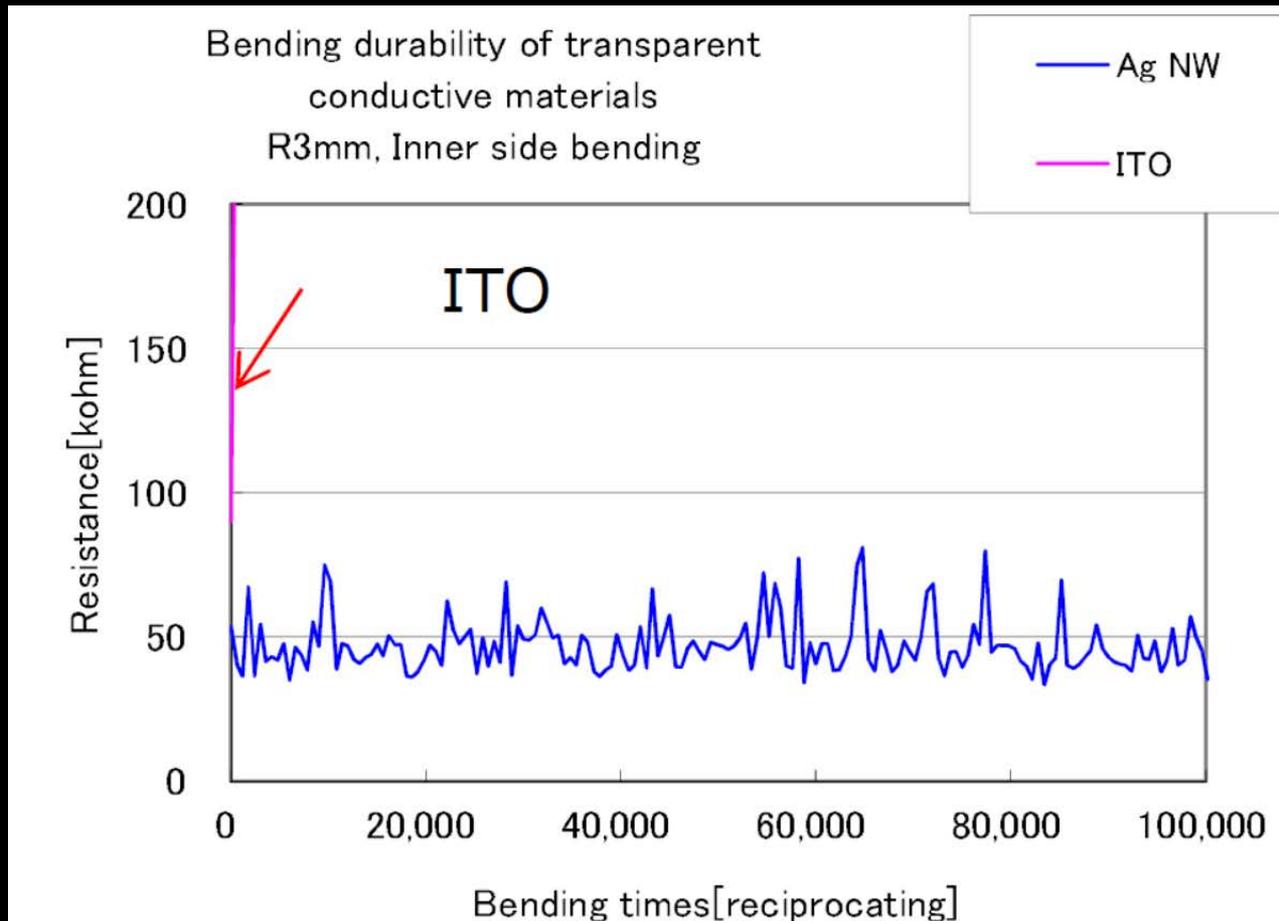
**OFF state**



**ON state**

*This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 314233 - <http://inlight-project.eu/>*

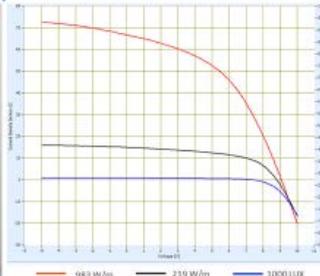
# Flexible and Bendable: passes 100,000 cycles at 3mm bend radius



Data Courtesy Nissha Printing Co.

# Flexible Transparent OPV Modules with Silver Nanowires

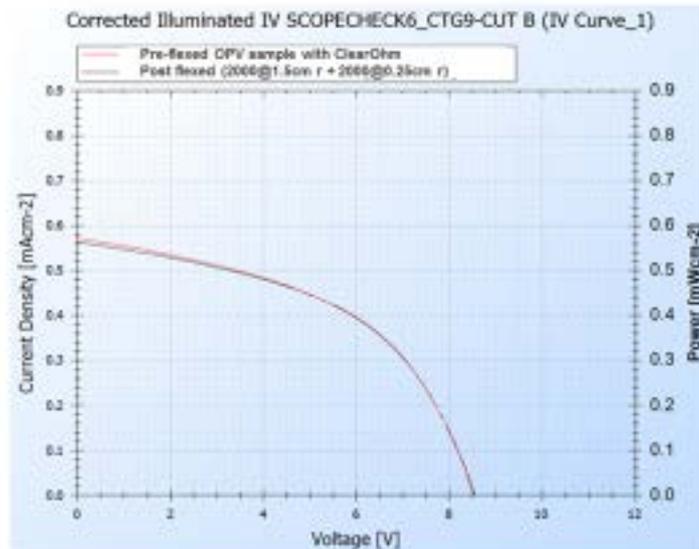
– Best large Area (300cm<sup>2</sup>) Transparent module has 60% FF at 1000 LUX



Eight19

## ClearOhm results – Flex testing effect

- Functioning, but not encapsulated module flex tested in air 2000 180° flexes at 1.5cm Radius
  - Result: still 100% functioning
- Same module section flexed a further 2000 times at 0.25cm Radius
  - Result: still 100% functioning
  - No change in module efficiency



Eight19

# Summary

- ClearOhm adopted as the transparent conductor of choice by leading touch panel makers
- ClearOhm enables cost effective production of OLED's
  - Large size tiles without metal grids eliminates process steps
  - Printing eliminates etching
- Improved performance and scalability for manufacturing
  - Wider process window enables scaling to G5/8 or R2R production
  - Control and design freedom to improve light extraction
- ClearOhm enables key differentiating features for OLED lighting
  - Flexible, formable and transparent devices
- Available in large volumes to support production

Thank You