Cambrios ClearOhm™ Transparent Conductors: Enabling Innovation in Touch, Displays, OLEDs and Solar Cells

Rahul Gupta

Senior Director Business Development

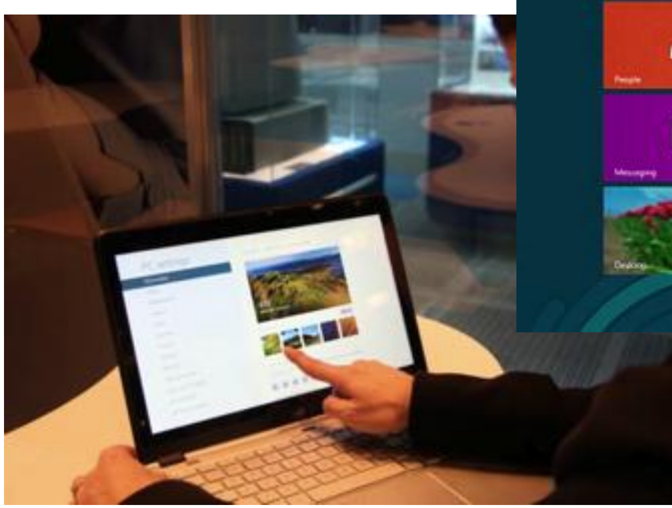
March 20, 2013

Agenda

- Applications of Transparent Conductors
- ClearOhm™ silver nanowire based Transparent conductors
  - Optical/Electrical Performance
  - Flexibility
- Working with ClearOhm material: Coating/patterning
- Commercially available Touch Panels using ClearOhm materials
- OLED/OPV Performance using ClearOhm electrodes
- Conclusions

Touch Becoming Ubiquitous

- SmartPhones & Tablets are everywhere
- Windows 8 is driving a touch interface into Ultrabooks and All-in-Ones



CAMBRIOS

Touch in New Form Factors and New Applications

New Applications, New Requirements

- New applications and innovations require:
  - Low Resistance (High Conductivity)
  - Flexibility: either for process or end product
  - Lower Cost
- Difficult to Achieve with ITO

CAMBRIOS

ITO The Incumbent Technology

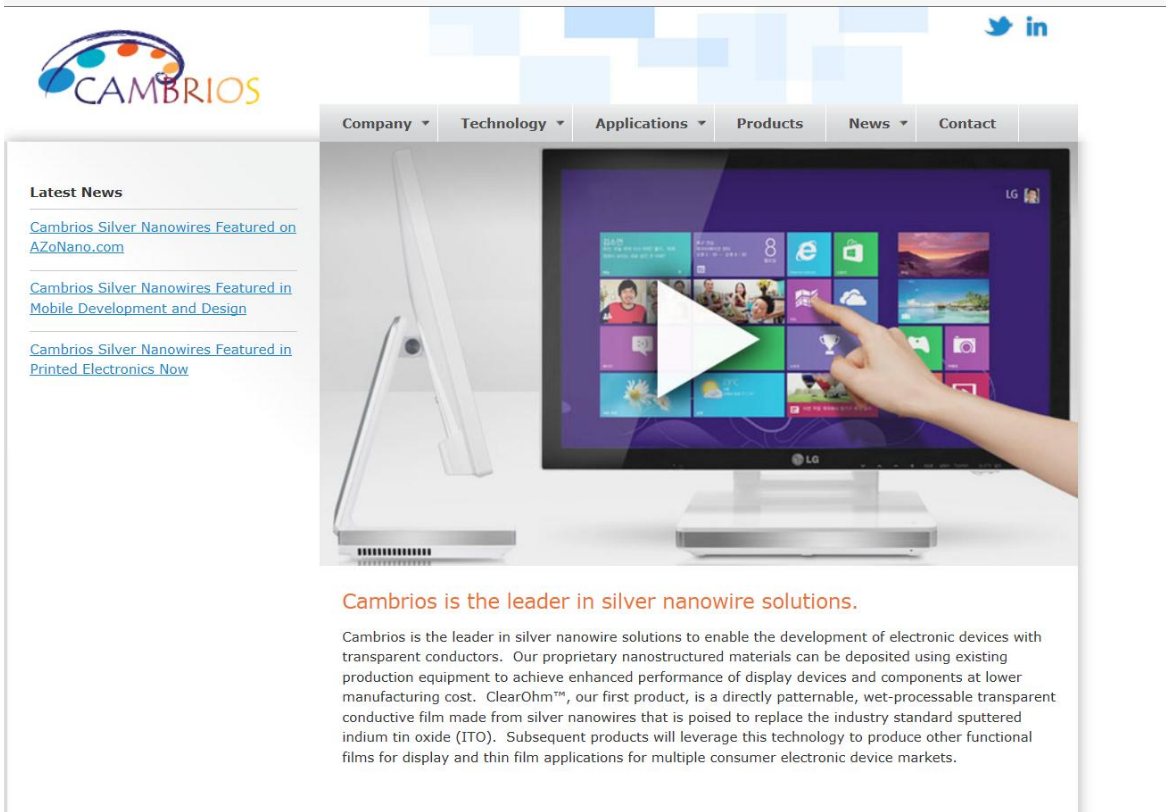
- Indium Tin Oxide (ITO) is the most commonly used transparent conductor
- ITO has many limitations
  - Expensive vacuum deposition
  - Limited throughput for low resistance
    - Many systems/huge investment
  - High temperature to get to good conductivity
    - Poor performance on low cost plastic substrates
  - Brittle so difficult to handle on flexible substrates
  - Rare volatile and politically sensitive
- New transparent conductor required

Cambrios Technologies Corp.

Leader in Nanotechnology Solutions for Transparent Conductors

- Founded in 2002 by scientists at MIT and University of California, Santa Barbara
  - Focus on developing solution processable transparent conducting materials
- Design and manufacturing in Sunnyvale, CA with offices in Japan and Korea
- Venture-backed startup with Key Strategic Partners
  - ARCH Venture Partners, Alloy Ventures, Oxford Bioscience Partners, Harris & Harris Group
  - Many strategic investors including Samsung, TPK
- Strong IP Portfolio: >175 pending patent applications, >22 issued or allowed patents
- Commercially used in Touch Sensors

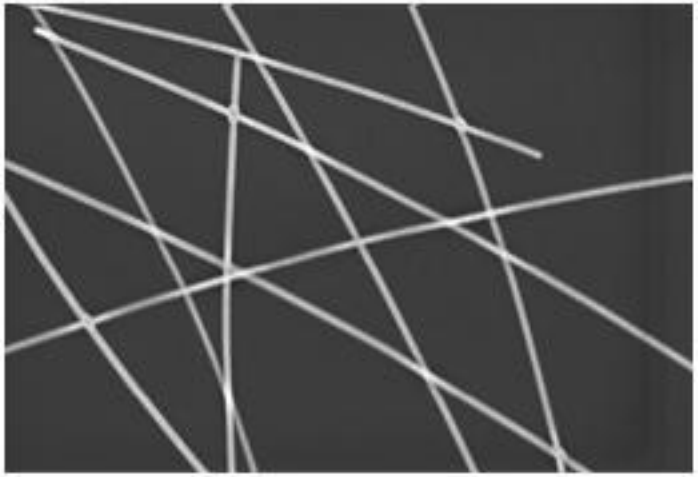
Company Video



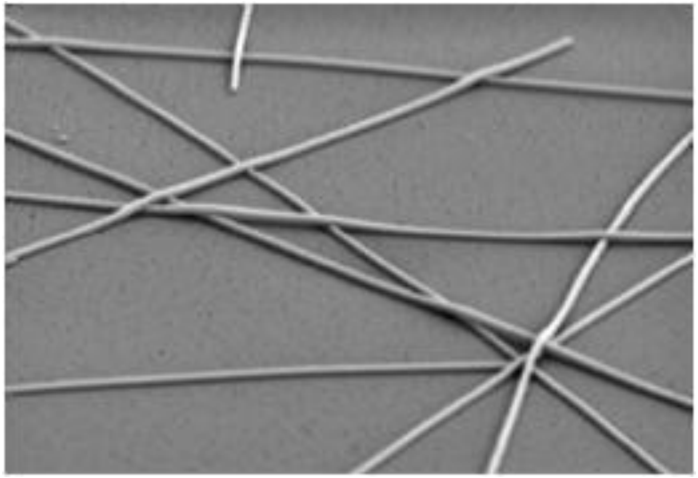
ClearOhm™ by Cambrios
Next Generation Transparent Conductor

- Silver Nanowires
  - Single crystal silver → High conductivity
  - Large spaces → High transparency
  - Inexpensive and easy to use

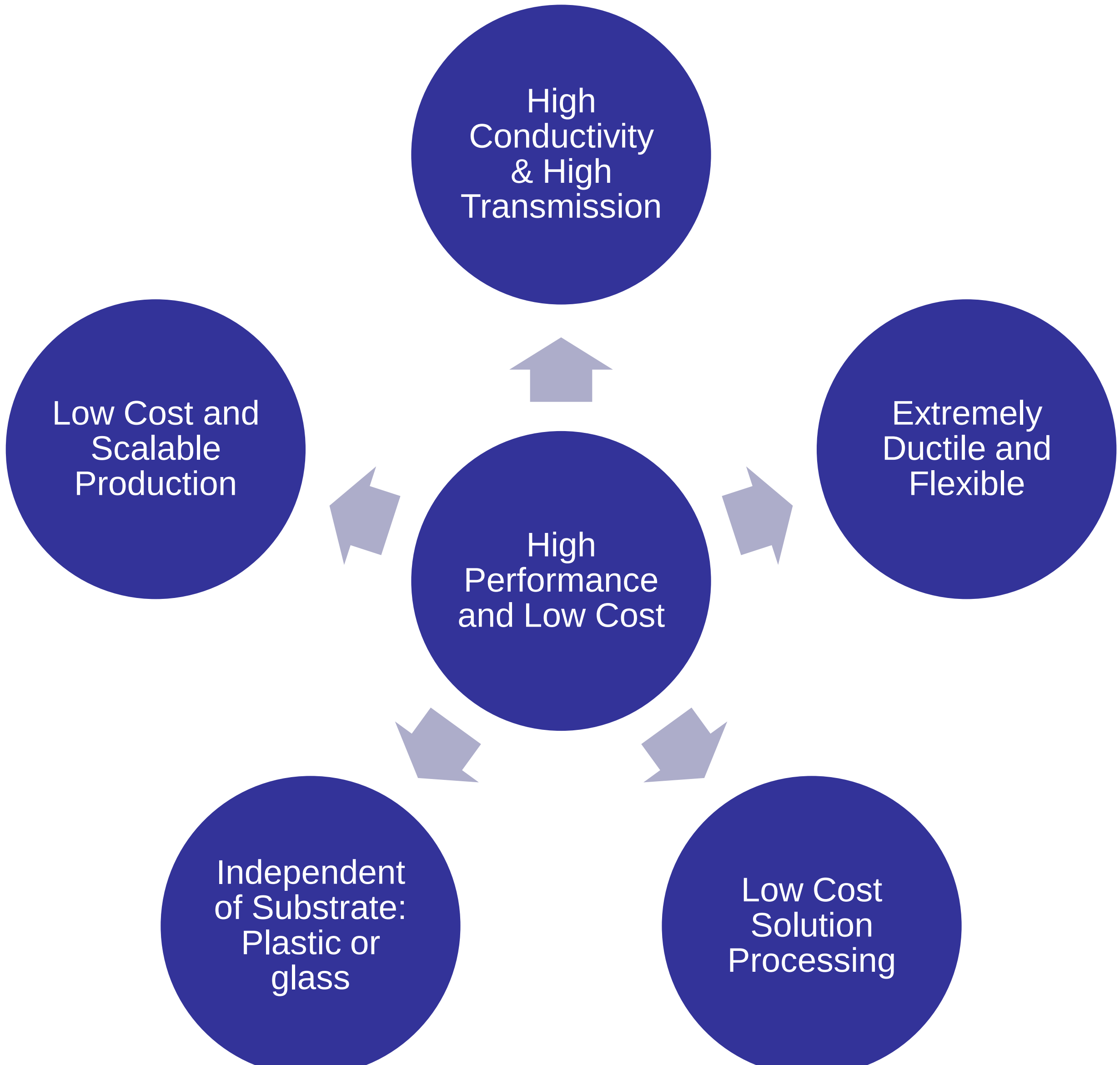
Plan View



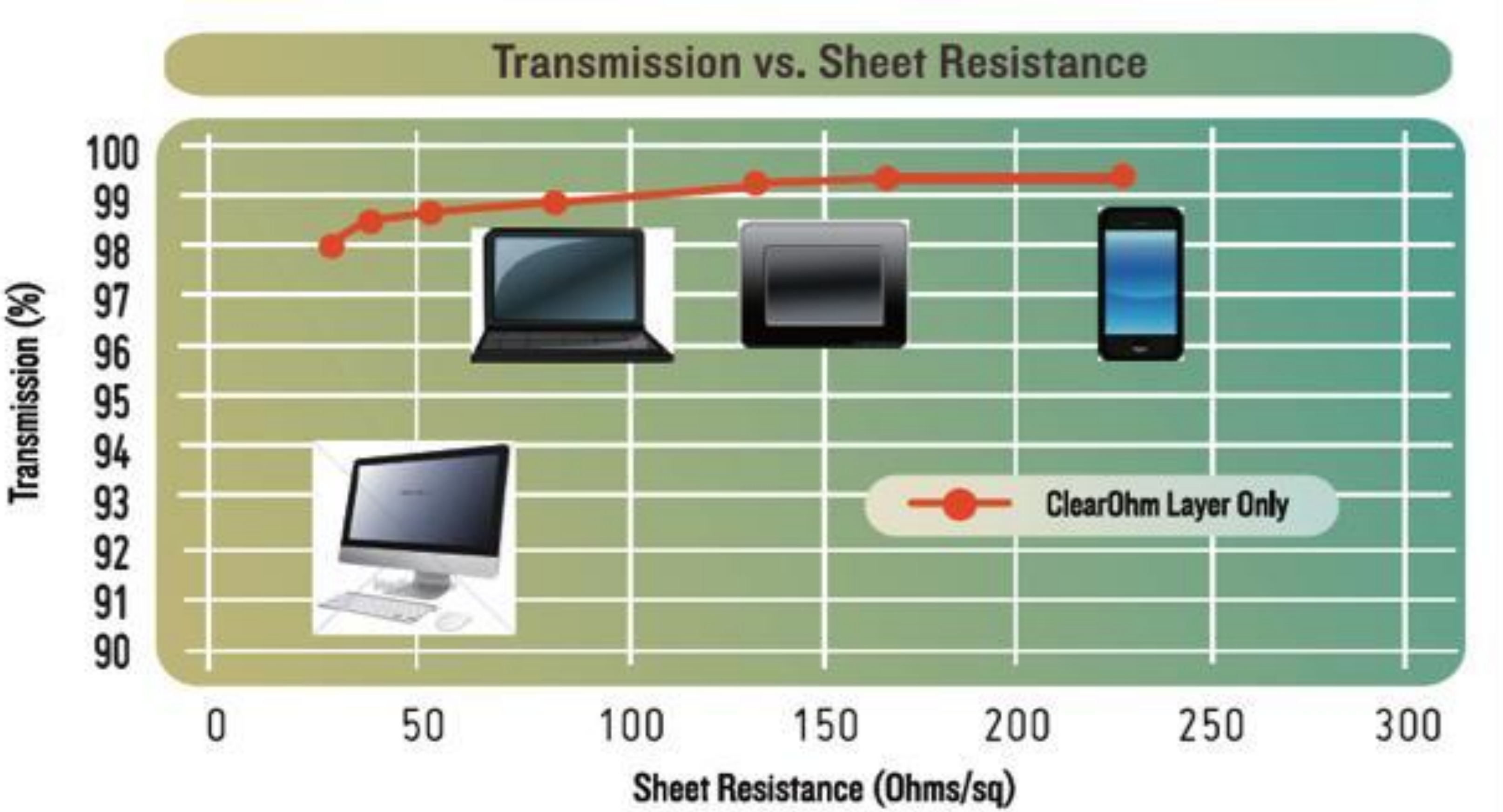
70 degree tilt



Core Product Strengths

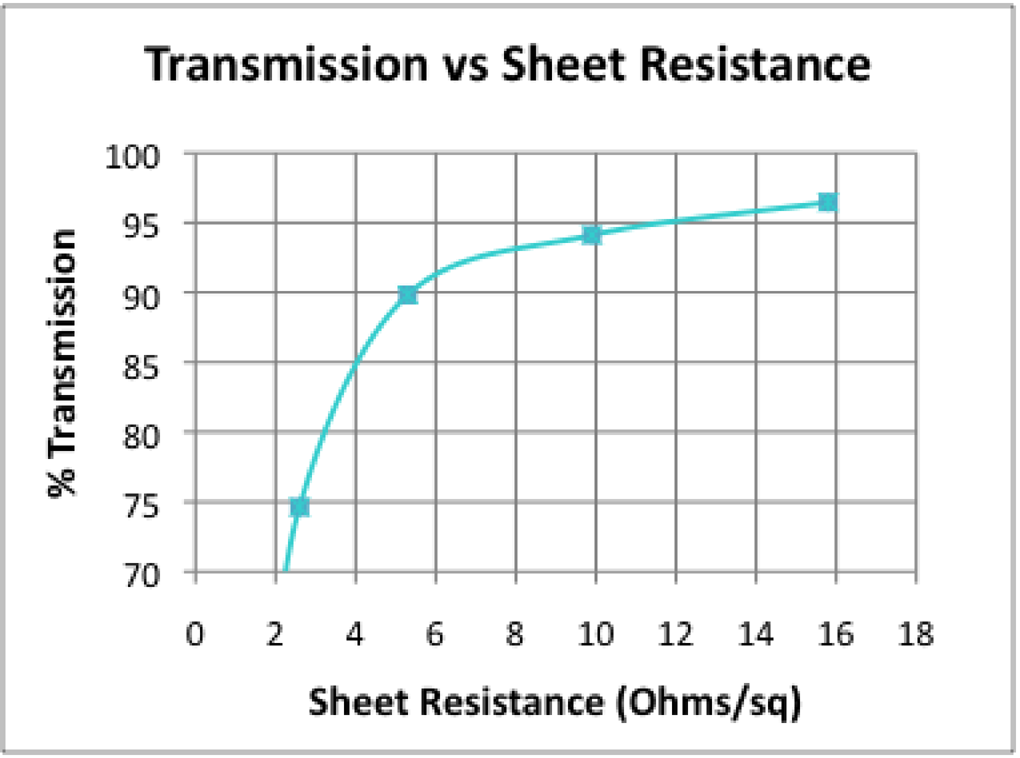


ClearOhm™ Transmission: Better than ITO



- >98% transmission down to 30 Ω per square
- Low sheet resistance (not available with ITO Film) enables many applications

Low Sheet Resistance with High Transmission for OLED/OPV

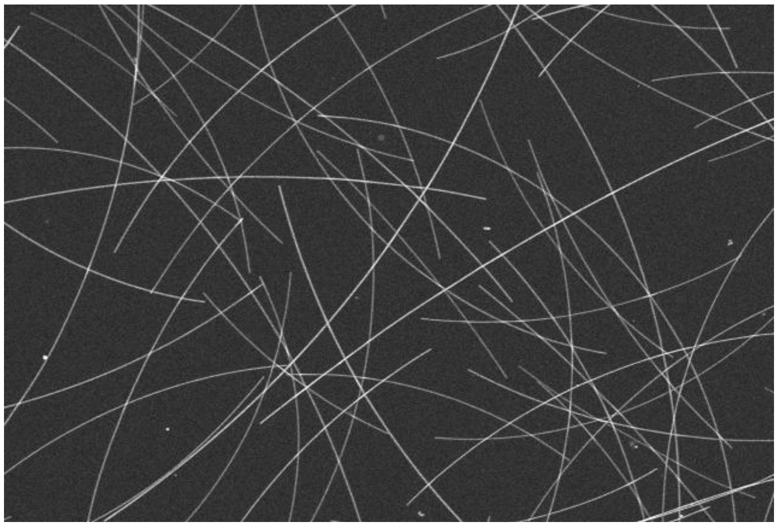


Spin coating on glass, air as reference; glass transmission 93.3%

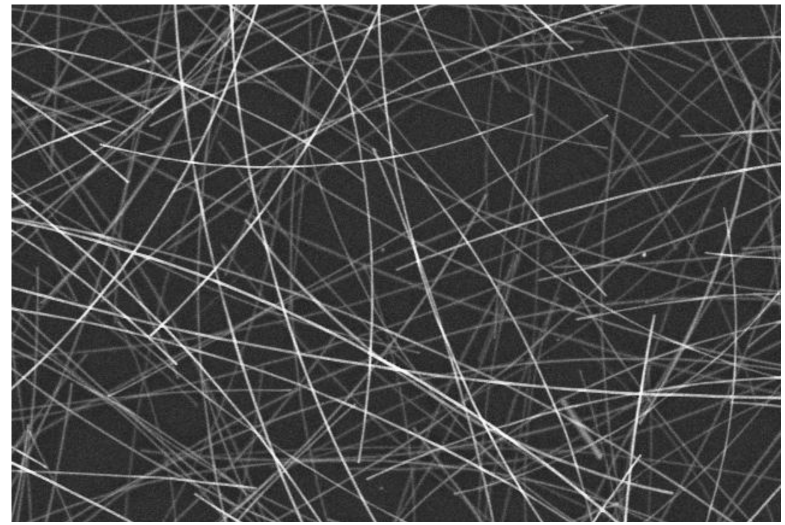
- High transmission even at low sheet resistance
- Great for large area OLED displays (TV) and lighting applications
- OPV top and/or bottom electrodes

Density of Silver Nanowires Determines Sheet Resistance

70Ω/□

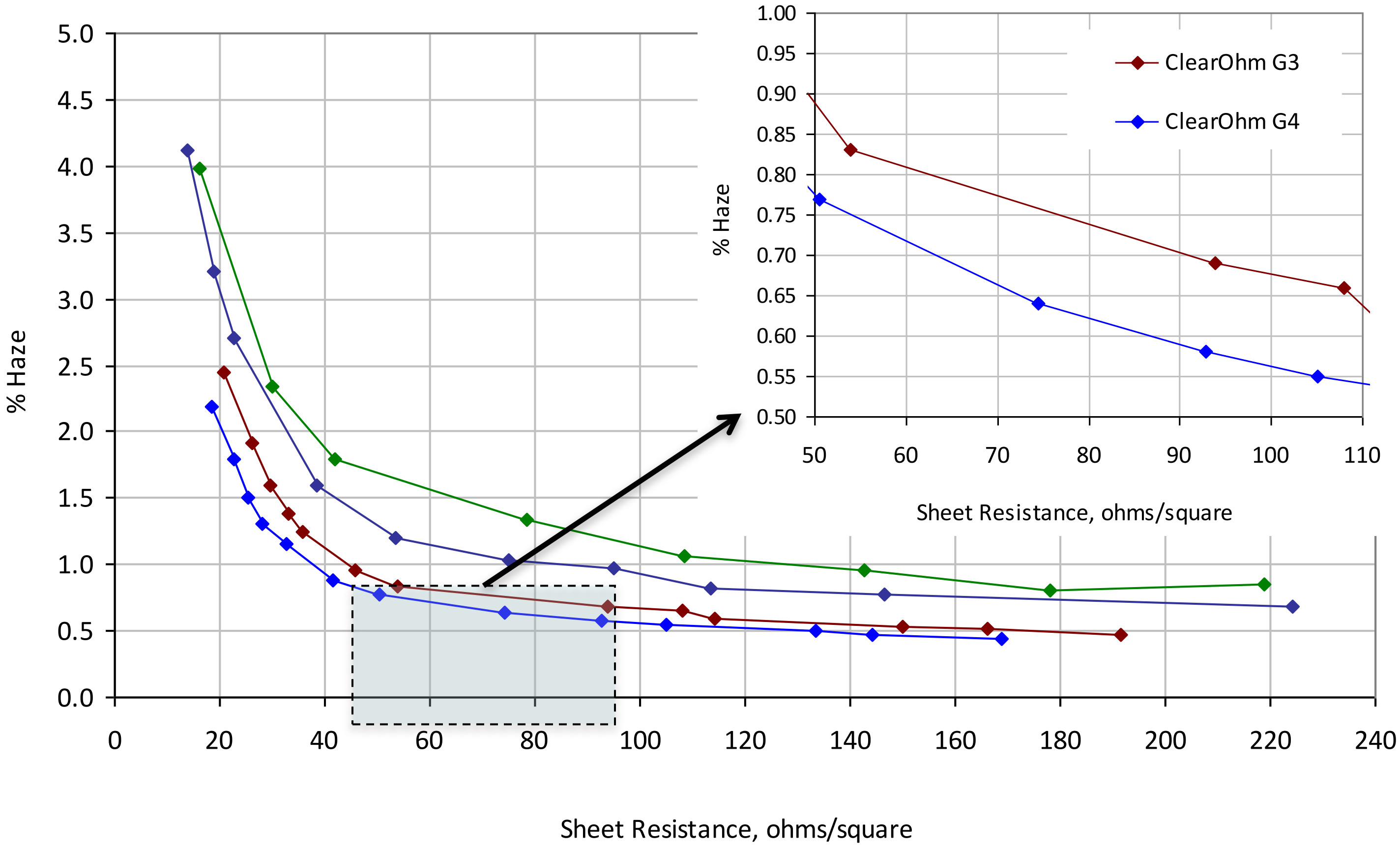


9Ω/□



- Higher nanowire density = Higher Conductivity
- Coating Throughput Independent of conductivity
  - Change ink concentration or wet film thickness

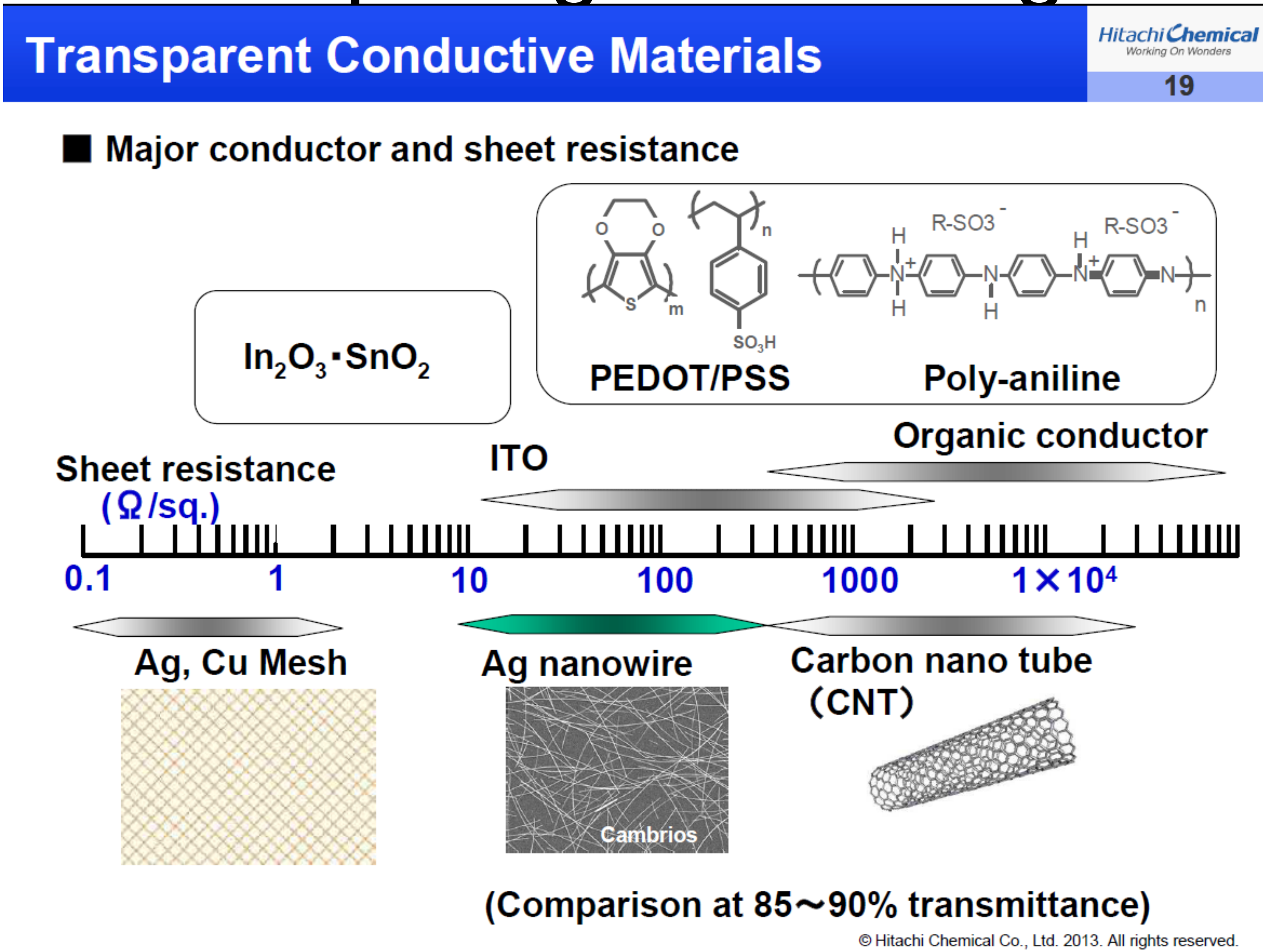
Optical – Electrical Performance: Haze



Haze Now Meets Requirements for Commercial Displays and Touch panels

CAMBRIOS

Competing Technologies



ClearOhm Electrodes Enable Flexible Displays and 2.5D/3D Shapes

AUO Flexible Epaper Display at FPD 2011

ClearOhm used as Pixel electrode

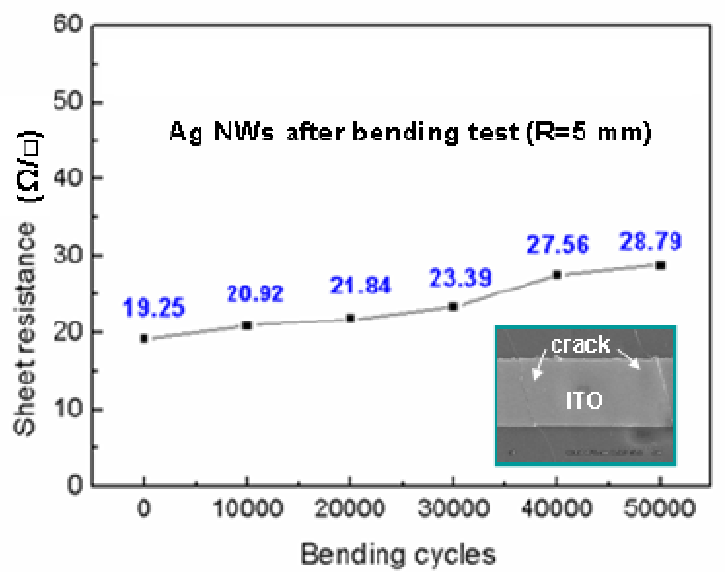


Figure 5. Ag NWs bending test at the radius of 5 mm.

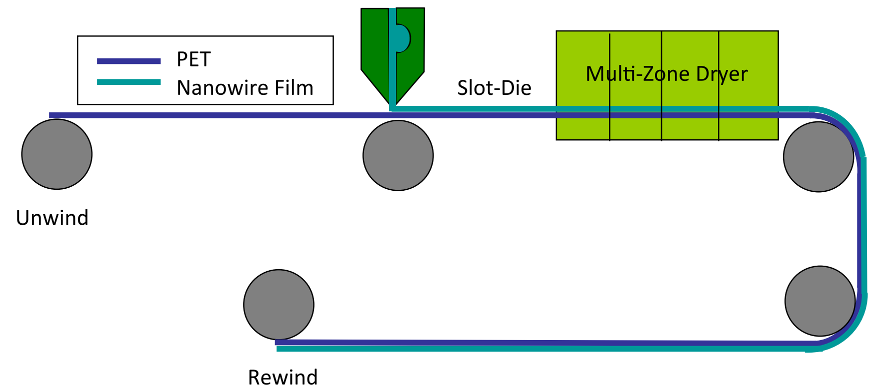
Transparent Silver Nanowire Film as Pixel Electrode for Flexible Electrophoretic Display

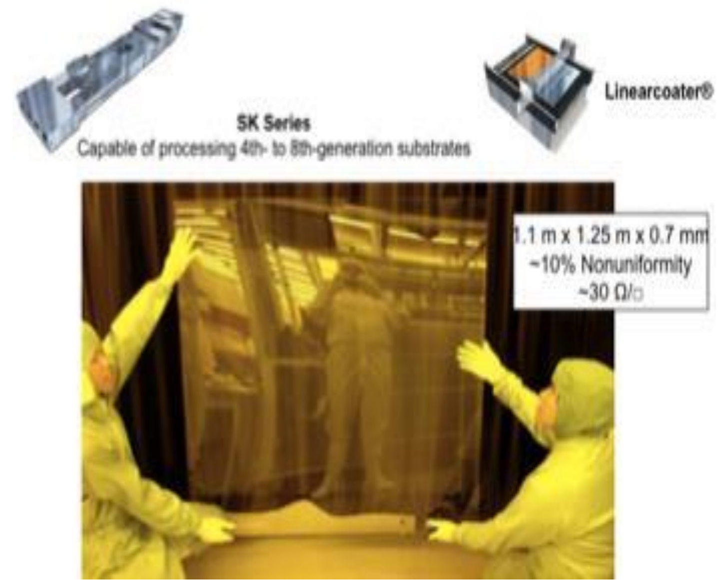
Shih-Hao Tseng, Shih-Hsing Hung, Keh-Long Hwu and Chih-Jen Hu, Wei-Ming Huang
AC Technology Div., AU Optronics Corporation
No.1, Li-Hsin Rd. 2 , Hsinchu Science Park, Hsinchu 30078, Taiwan, R.O.C.

SID Digest 2012

ClearOhm™ Coating Materials

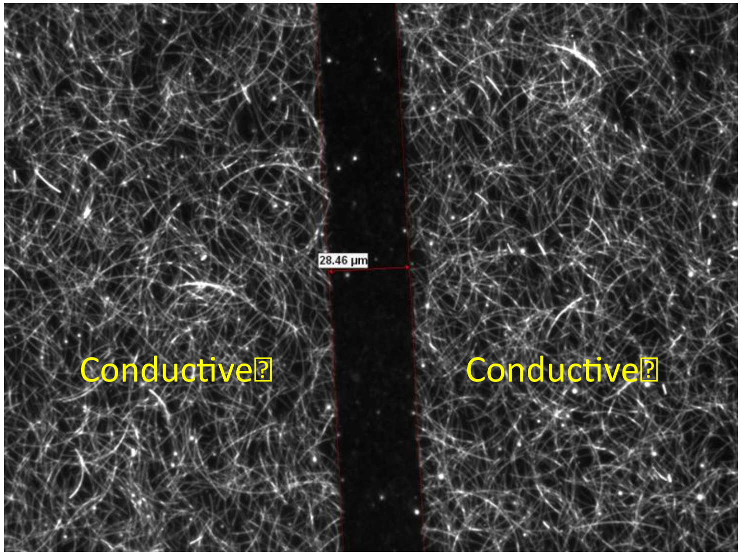
- ClearOhm Inks can be spin coated or slit coated
- Solution Coating for
  - Low Cost Process
  - High Throughput
    - 15-20 m/min R2R coating
    - 1.5m web ➔ >1 M m^2/month
- Compatible with Plastic substrates like PET
  - Baking temperature can be 100C or less
- Compatible with sheet process on glass or plastic

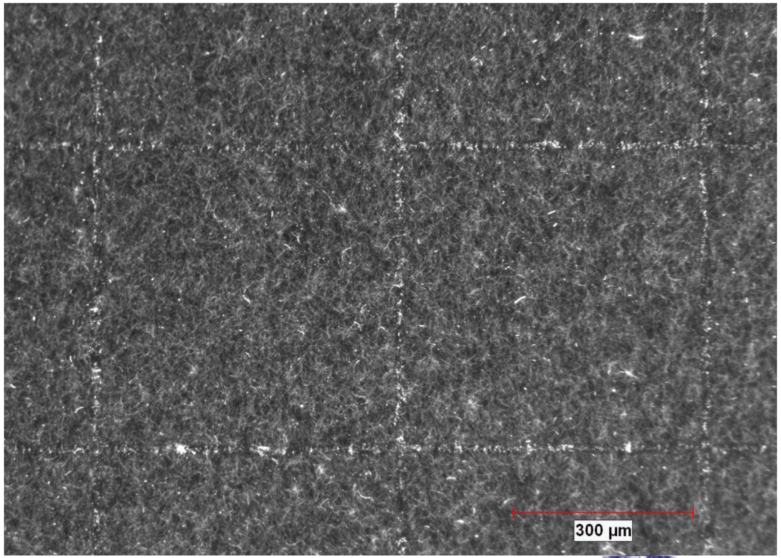




Patterning ClearOhm Layers

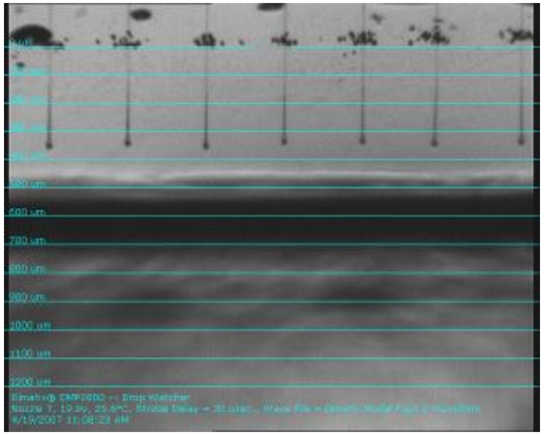
- ClearOhm can be patterned using
  - Photolithography and wet etching
    - Similar to ITO
  - Laser patterning



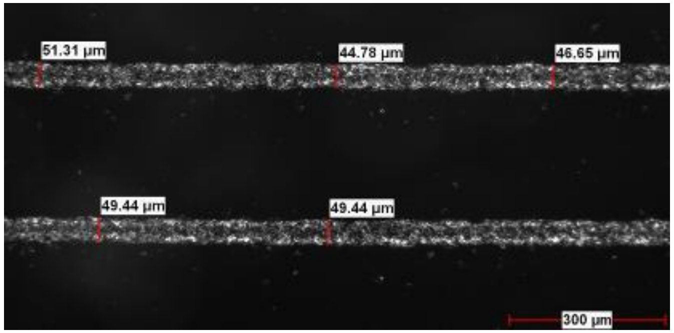


Printable ClearOhm™ Inks

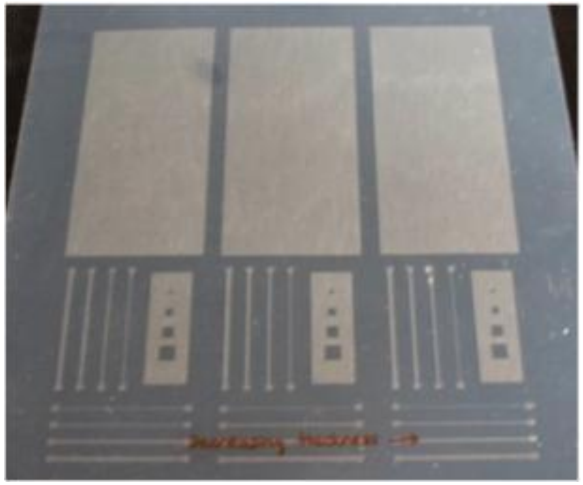
Inkjet Printing



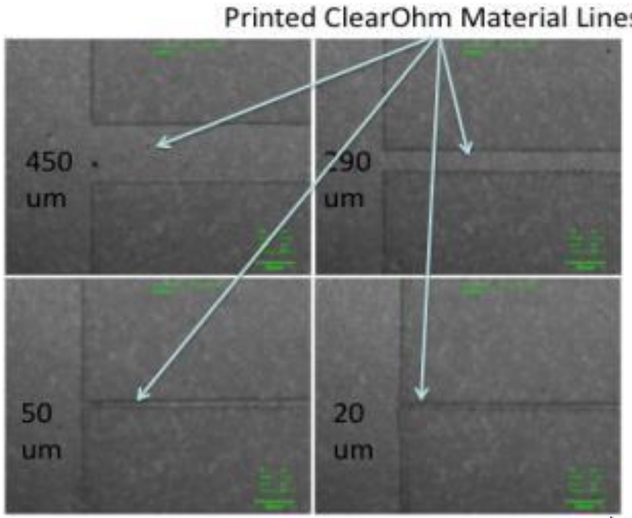
Screen Printing



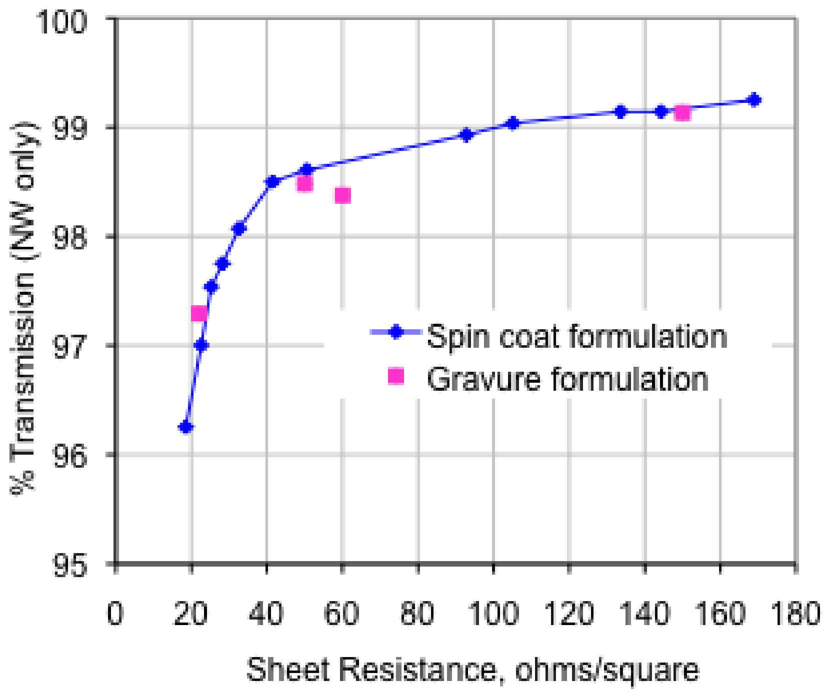
Gravure Printing

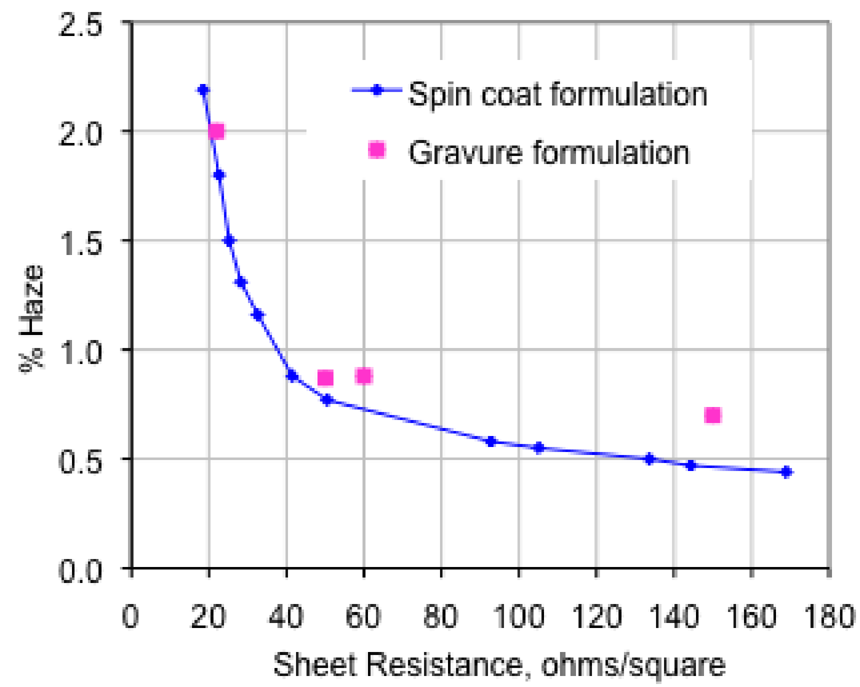


Reverse Offset Printing



Direct Printed ClearOhm Inks: Gravure

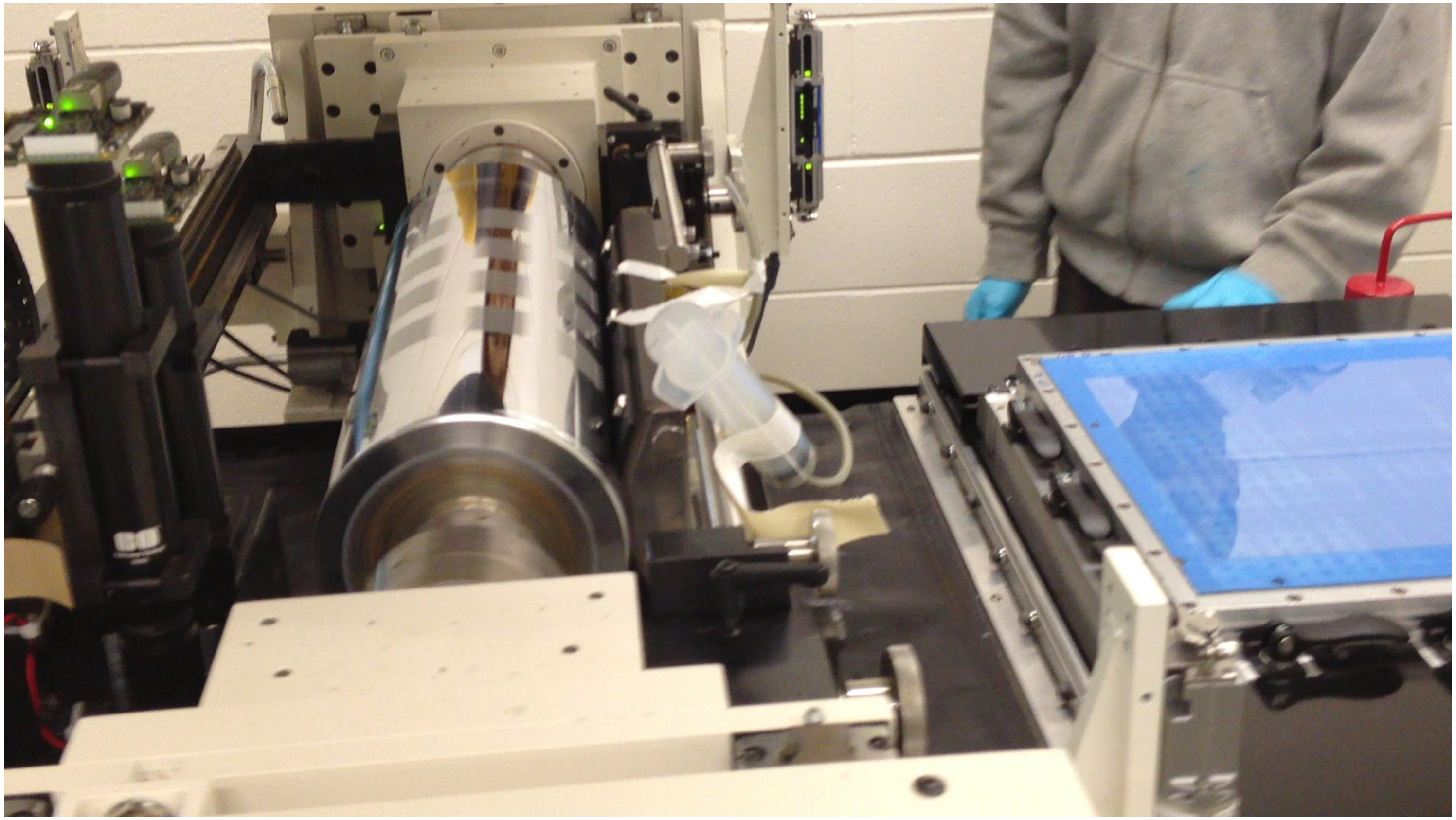




Haze, transmission, and sheet resistance of printed gravure formulation match values for spin coated formulation

CAMBRIOS

Printing on Rigid Glass Using Accupress (Western Michigan)



Idle speed is 100 rpm
Cylinder is 150 mm in diameter
Print speed is 1.2 meters/second

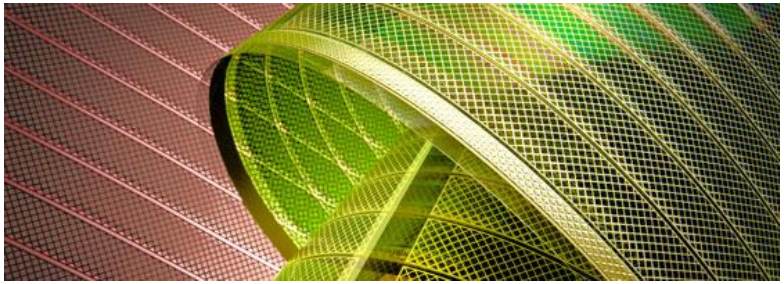
Applications and Target Markets

Touch Sensors

OLED Lighting

Displays

Solar Cells



Cambrios Products

- Solution processable transparent conductive coating material
- Transparent conductive film produced by value-added coating companies

ClearOhm™ Ink

ClearOhm™ Film

Sold bv Cambrios Partners

ClearOhm^{TM} Enabled Films

OKURA

TORAY

Innovation by Chemistry

銀ナノワイヤー透明導電フィルム

SILVER NANOWIRE TRANSPARENT CONDUCTIVE FILM

LG

Life's Good

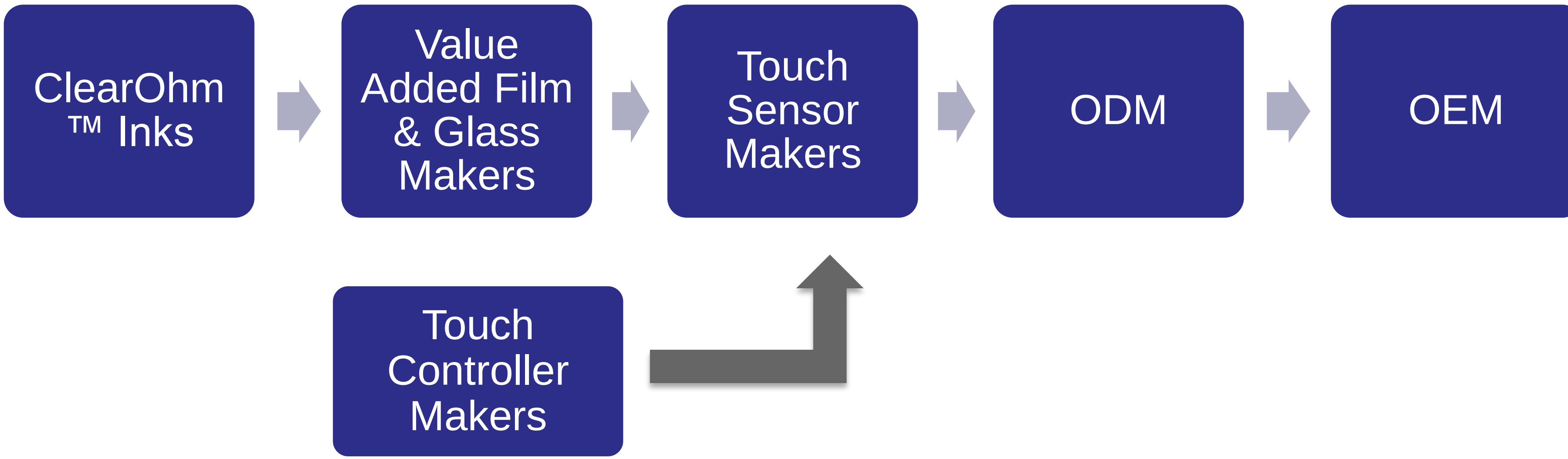
Shin-Etsu

Hitachi Chemical

Working On Wonders

TRANSPARENT CONDUCTIVE TRANSFER FILM (under development)

Touch Panel Supply Chain Using ClearOhm™ Material



Windows 8 Certified Touch Panels in Production Q4 2012

Touch Panel Supply Chain Using ClearOhm™ Material is ready for Production

ClearOhm™ Inks	Value Added Film Makers	Touch Sensor Makers	ODMs & OEMs
Cambrios	Okura, Toray, DIC, HCC, ShinEtsu	LGE	
	LGE and other Korean suppliers	eTurboTouch	
	China and US based suppliers	CNi	
		Nissha Printing	
		Shin-Etsu	
		Others	

Recent Phones using ClearOhm™

Huawei Ascend on
Sprint

NEC MEDIAS X N-07D on
NTT DoCoMo Network

- Proof of cost structure and commercial quality
  - Products span low end to high end
- Excellent pattern visibility and glass-like appearance

LG Announces World's First ClearOhm™ Film-based AiO PC

- Fast response enabled by low resistance ClearOhm film
- Windows 8 Certified
- Thin and light sensor unachievable with ITO
- Validates performance and value proposition for large-area touch panels

LG V325 23" AiO PC

Some more new Products

LG

LG ET83 TOUCH 10 MONITOR
OPTIMIZED FOR WINDOWS 8

Available At Frys

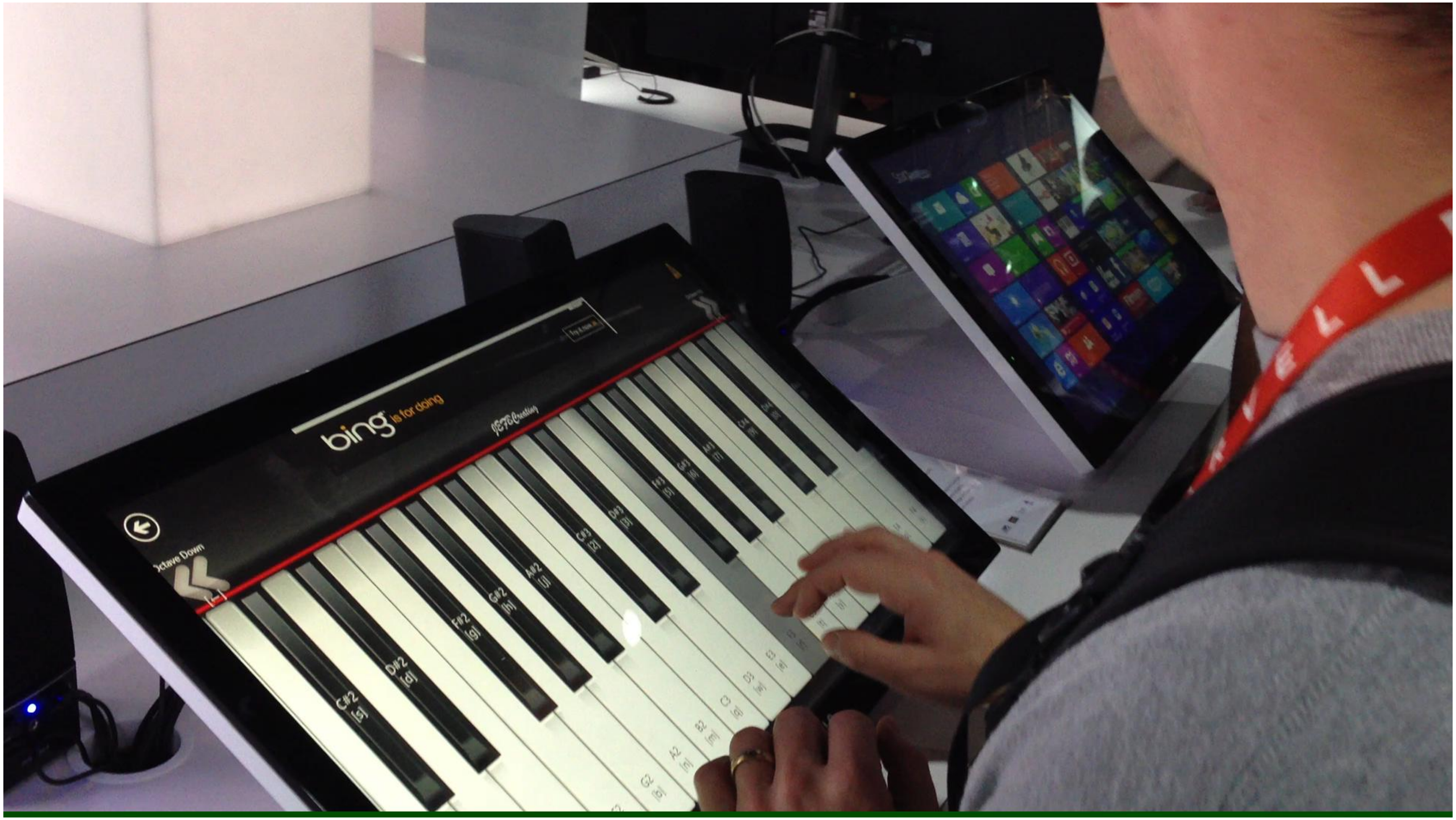
Enables Full Touch Experience Even With Non Touch Enabled Laptops And Desktops

GVISION

L15AX 15" Point Of Sale Touch Monitor

CAMBRIOS

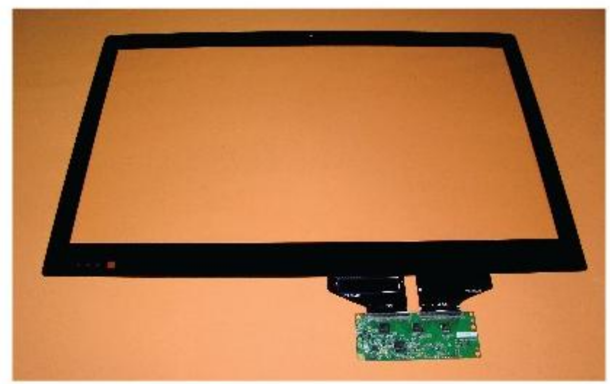
Coming Soon : LG ET63



Ecosystem Partners Announced at CES 2013

Intel Ultrabook Form Factor Reference Design

Windows 8 Compatible Touch Sensor Modules Using Cambrios ClearOhm™ Material



Thin And Light 23.6" G1F Touch Sensor For AIO And Monitors

Large New Markets for Transparent Electrodes

OLED Displays

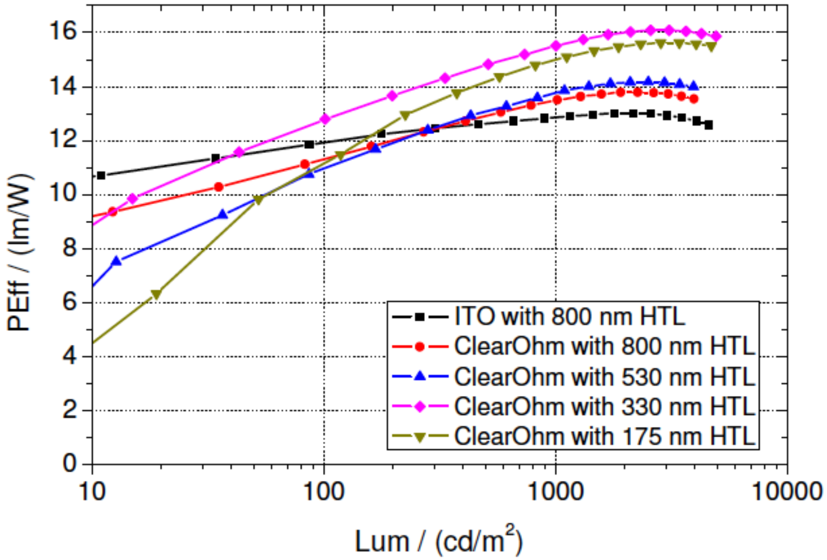
OLED Lighting

Thin Film Solar

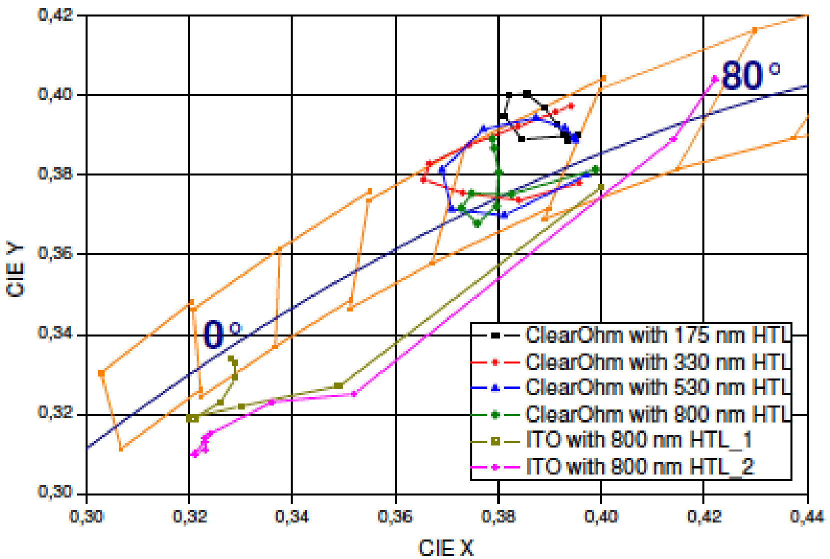
Emerging Markets:
OLED Value Proposition

- Same or better efficiency
- No angle dependence of color
- Lifetimes similar to ITO
- R2R manufacturing for lighting

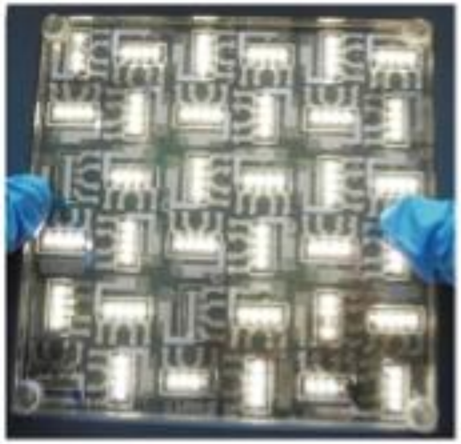
Higher Efficiency vs.ITO



Small Change in color with angle



Novaled AG



42 Lm/W 5cm x 5cm Lighting Tile

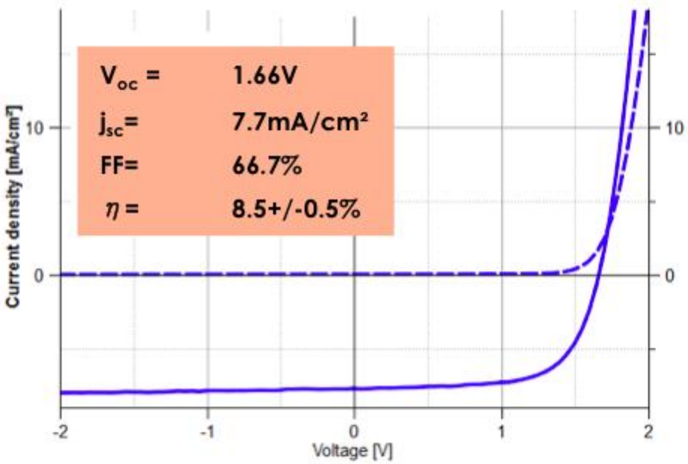
Sample	Current [mA]	Voltage [V]	CIE X	CIE Y	Power efficiency [lm/W]	Quantum efficiency [%]
S00	21.0	8.33	0.512	0.430	43.6	53.2
S01	21.0	8.33	0.514	0.429	42.8	52.4
S10	21.0	8.33	0.510	0.431	44.3	53.6
S11	21.0	8.33	0.511	0.432	43.3	52.5
ITO ref.*	3.3	8.23	0.442	0.421	47.4	54.5

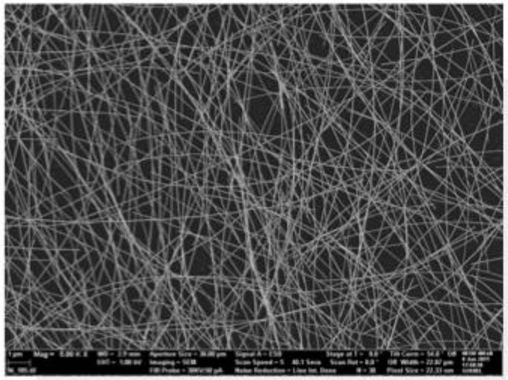
3 Layer stack
Anode Sheet Resistance: 10 ohms/sq

~8.5% Efficiency OPV Cell Using ClearOhm™ Bottom Electrode

Heliatek®
Say hello to solar. Wherever you are

Vacuum deposited pin-tandem cell (>1cm²) on PET with Ag-nanowire electrode (Cambrios)





- **Efficiency 8.5(+/-0.5)%** according to Heliatek-internal characterization* (similar performance to ITO on PET)
- high FF, low series resistance, low leakage current

* no explicit mismatch correction; error range estimated from previous experience with independent certification (9.8% on glass) for the same stack

Summary

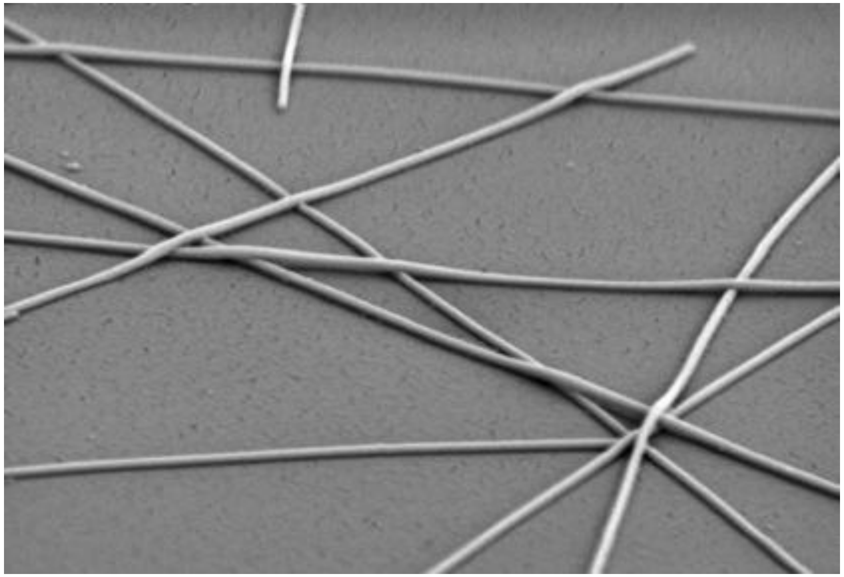
- ClearOhm Material is replacing ITO: already used in commercial Touch Panels, enabling large area touch panels
  - Large Supply Chain is coming online
- ClearOhm material can be used as an effective transparent electrode for OLEDs, OPV and other Applications
- Printable ClearOhm™ electrodes show promise, needs further development

CAMBRIOS

BACKUP

Emerging Markets:
Heliatek Flexible and Transparent OPV

- World record for organic photovoltaic
  - 10.7% efficiency
- Production facility under construction



Cambrios Ag-NWs + Clevios HILs for OLED-Anodes

Cambrios ClearOhm™ + Heraeus F-CE based ITO Free OLED's

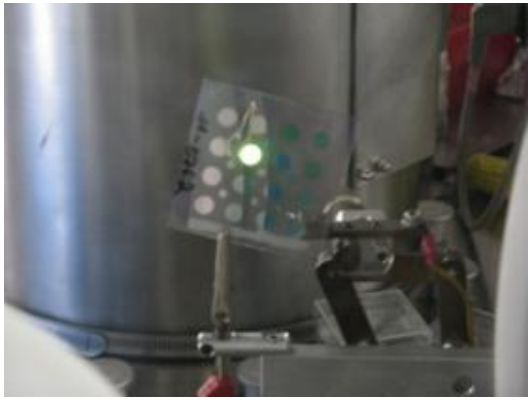
ClearOhm™ Low Resistance Transparent Electrode

+

Clevios FCE planarizing HIL

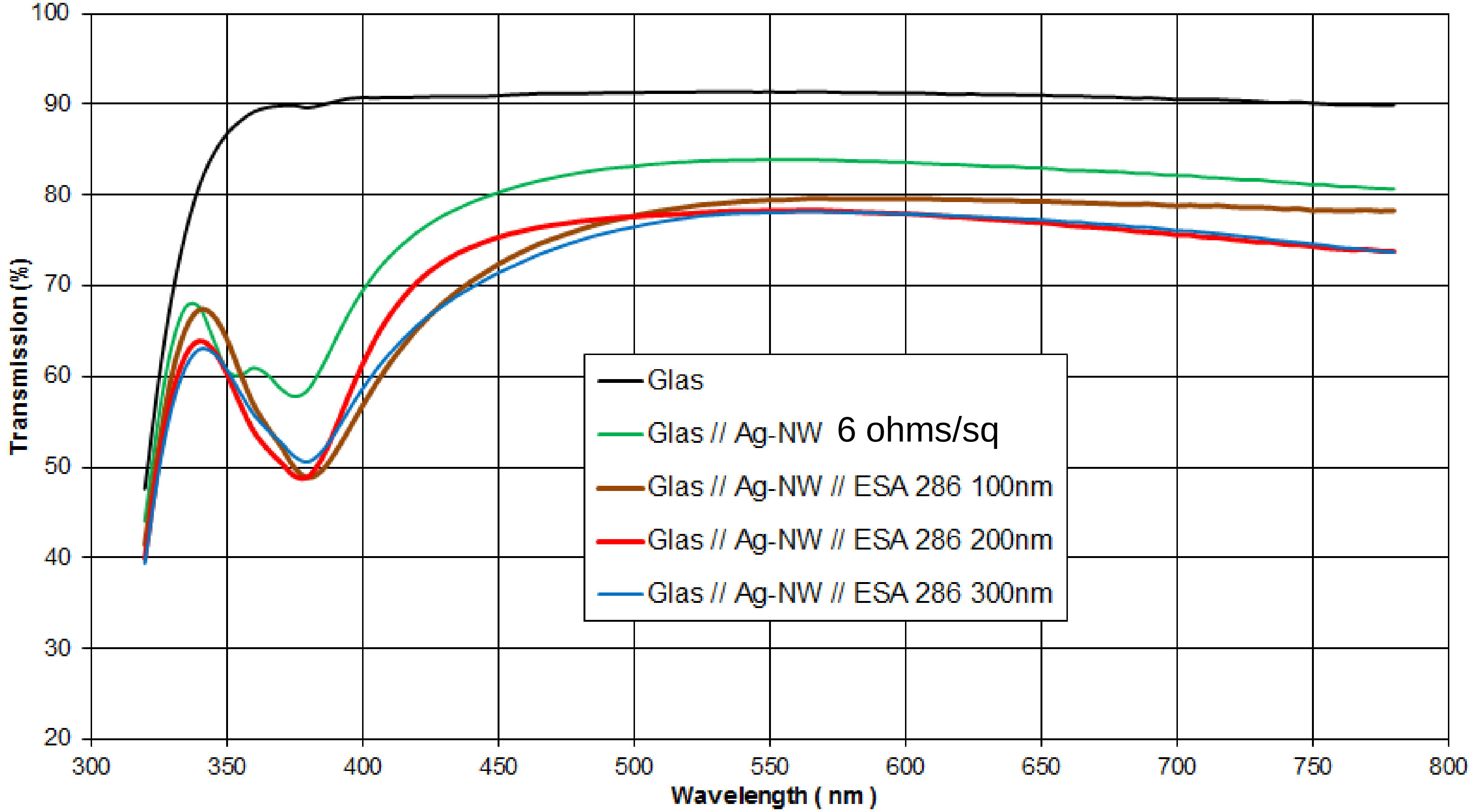
→

Efficient and Stable ITO Free OLEDs



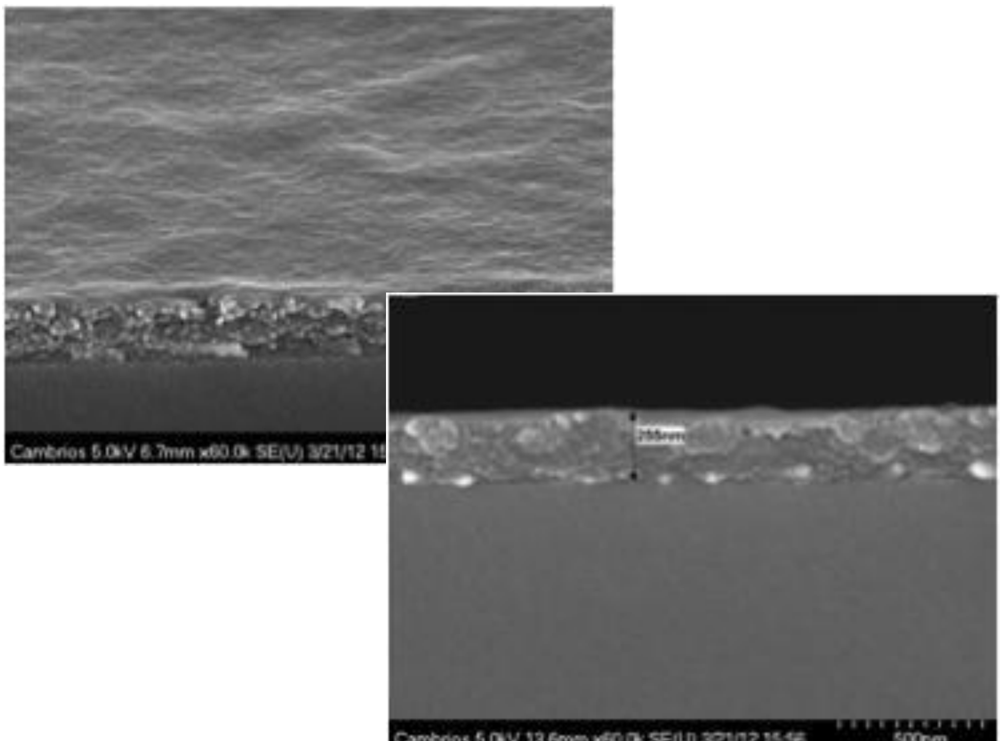
Heraeus CAMBRIOS

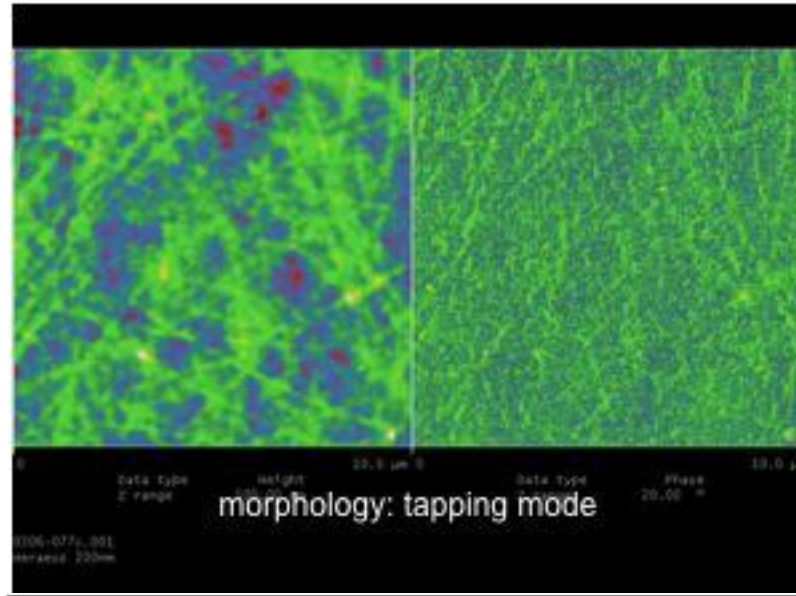
ClearOhm + Clevios F-CE UV-Vis Spectra

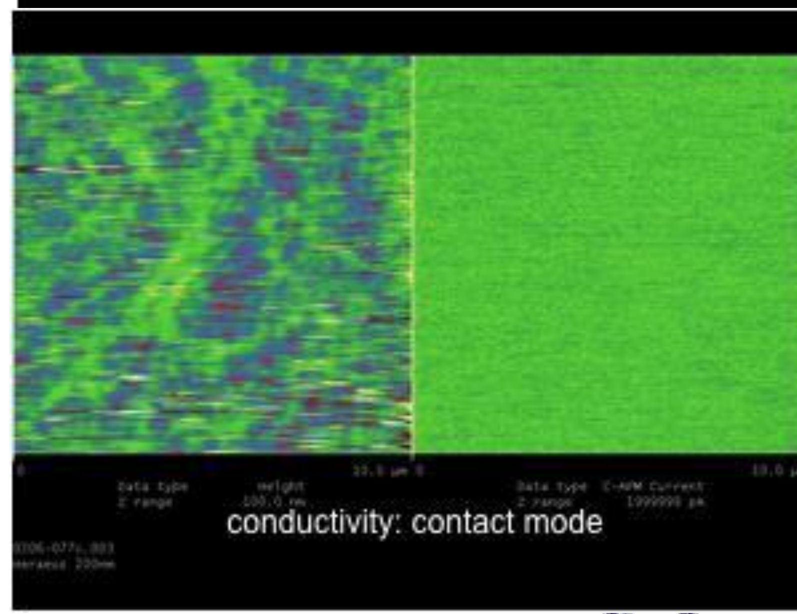


ClearOhm + 200nm F-CE

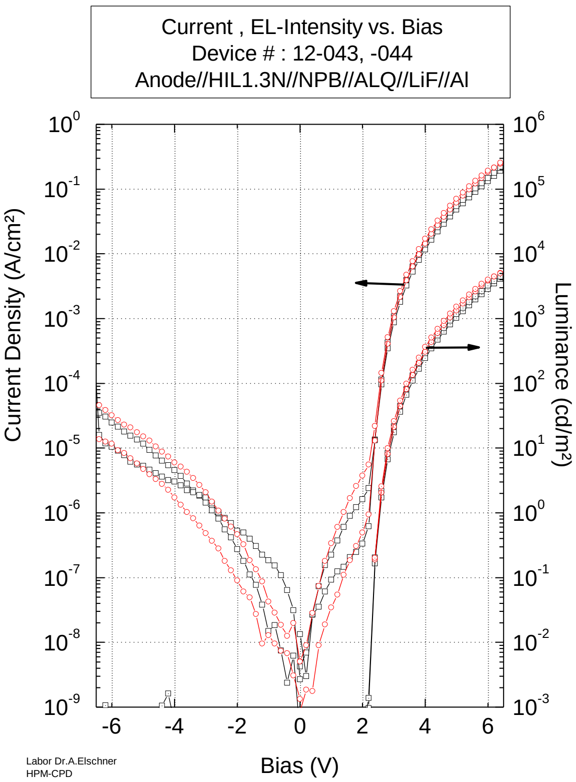
- SEM: Conformal coating, no spikes
- AFM 25μm scan:
  - Rz = 85.3nm, Rq = 8.6nm
  - Conductive AFM: uniform conductivity

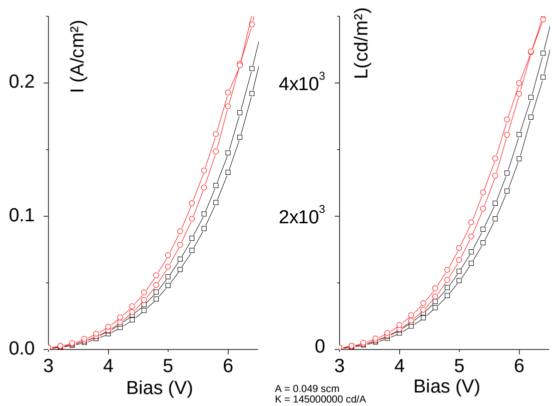


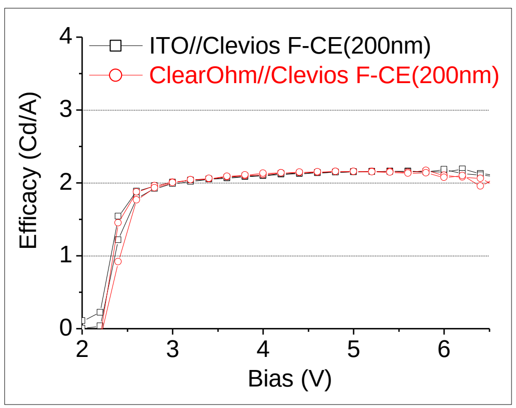




ITO//F-CE vs. Ag-NWs//F-CE: Similar IVL Performance







Device Preparation:

OLEDs are prepared in comparison on ITO and on Ag-NWs.

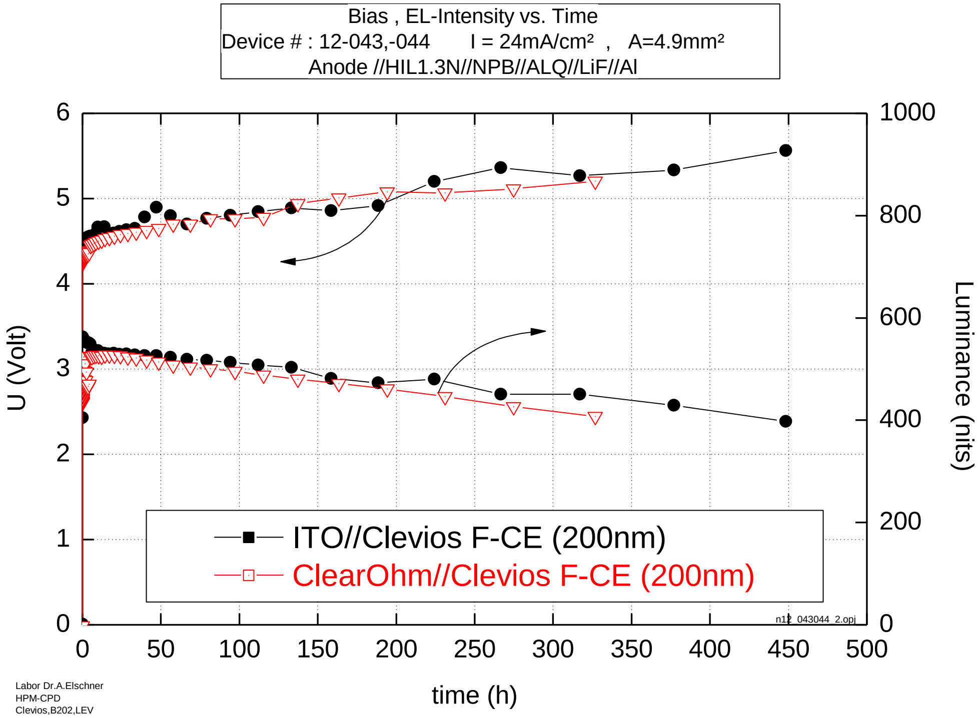
A 200nm thick Clevios F-CE layer is deposited for surface planarization first followed by a 50nm thick layer of Clevios HIL1.3N to improve device lifetime.

IVLs:

Total device current and leakage current are almost the same for both anodes

ITO//F-CE vs. Ag-NWs//F-CE: Similar Lifetime

Anode //HIL1.3N//NPB//ALQ//LiF//Al



Device Lifetimes:

The lifetime tests are conducted at constant current conditions
(j = 24 mA/cm²)

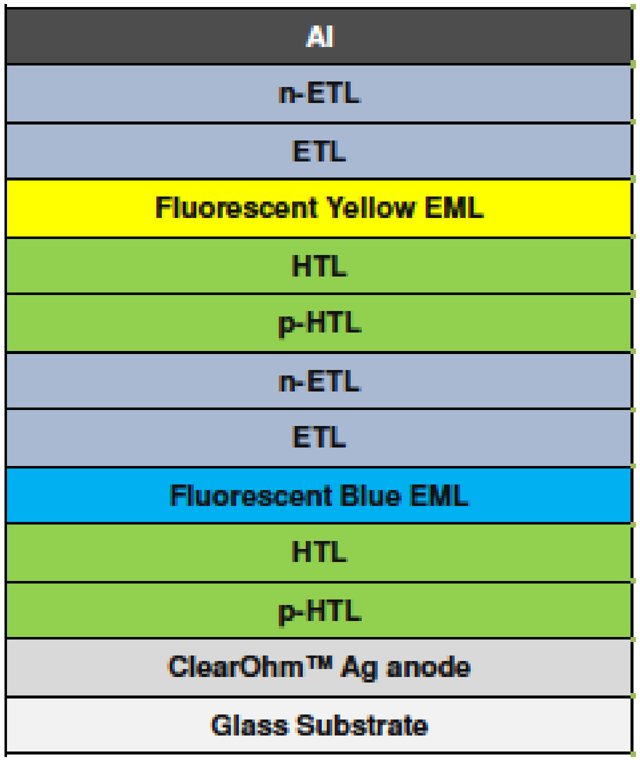
Devices were kept during the test in a N2-Glovebox w/o any further encapsulation

➔ No significant difference in lifetimes for ITO//F-CE - and ClearOhm//F-CE - anodes within the accuracy of experiment

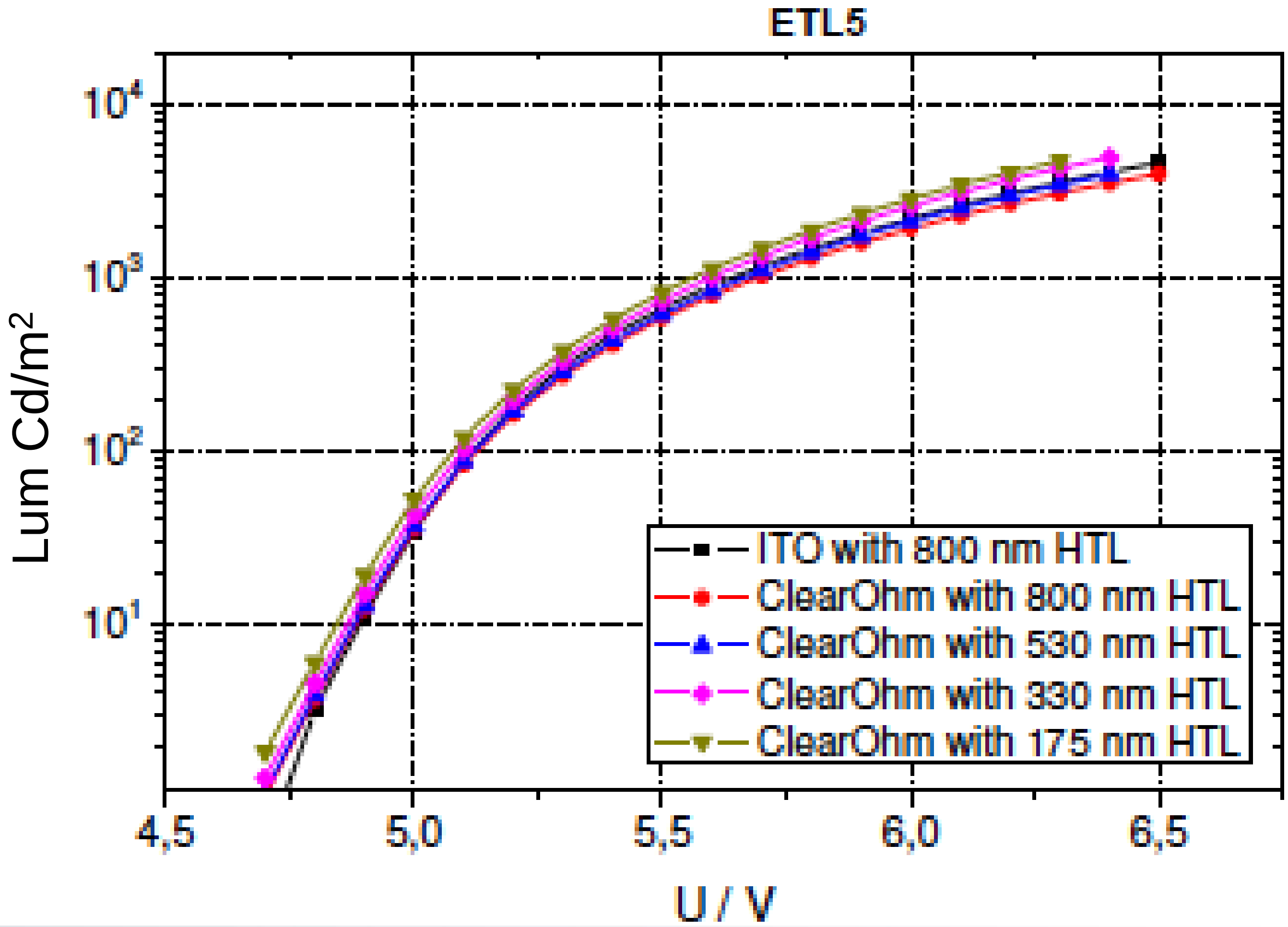
OLED's with ClearOhm and Small Molecule HIL's

Work done in collaboration with NOVALED

2 Color fluorescent tandem stack

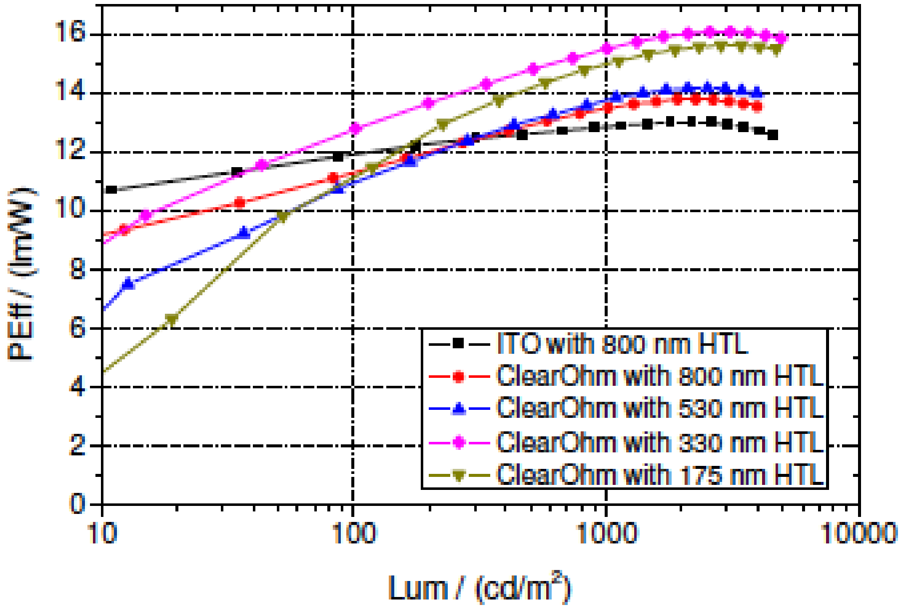


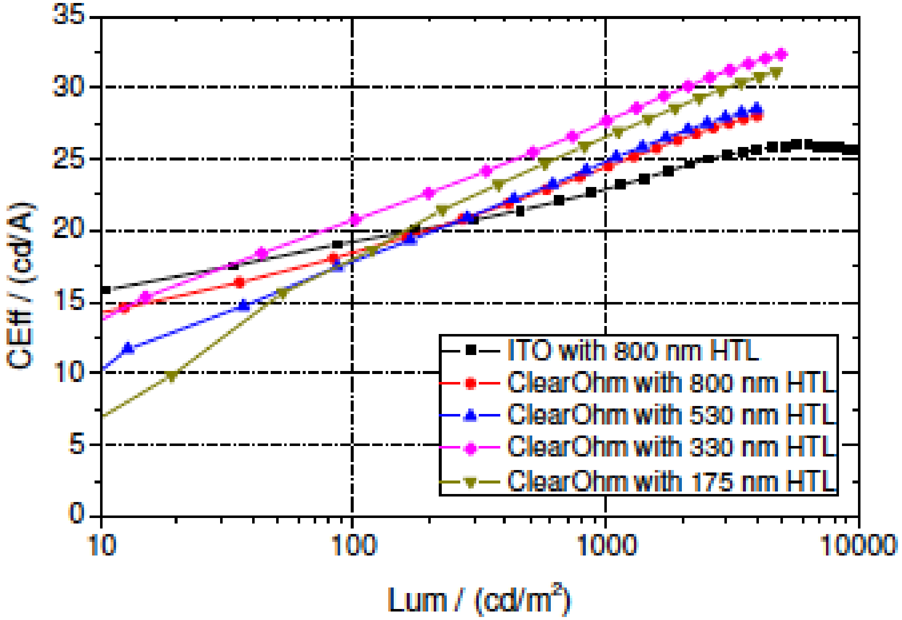
Similar Operating Voltage as ITO



Operating Voltage: 5.6 – 5.7 V for 1000 Cd/m2

Similar Power and Current Efficiency as ITO

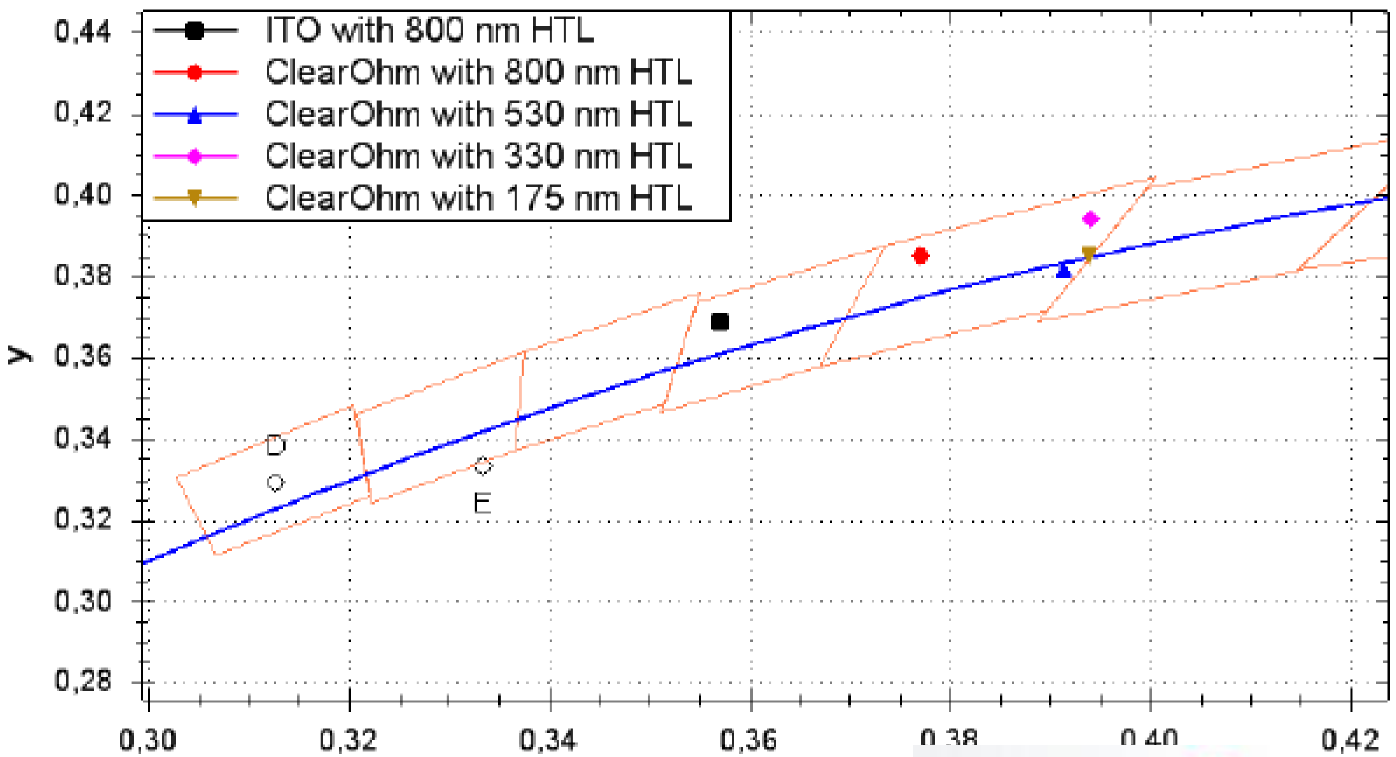




- ~ 10% higher power efficiency for the same stack as ITO
- >20% improvement with thinner HTL: no data for ITO with thinner HTL
- Need to optimize stack to maximize scattering of light from nanowires
- Cambrios developing internal light extraction layers in combination with nanowires

Small Color Change with thickness of stack

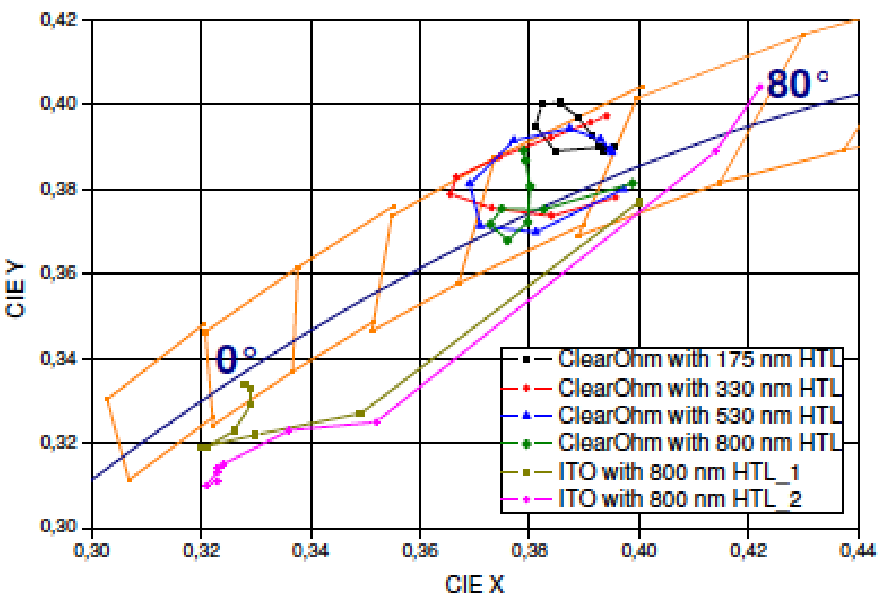
- Device color within DOE Energy Star quadrangle CCT 4000K
- Small color change with thickness ➔ Weak microcavity
- Tolerance to process variations ➔ No binning in production

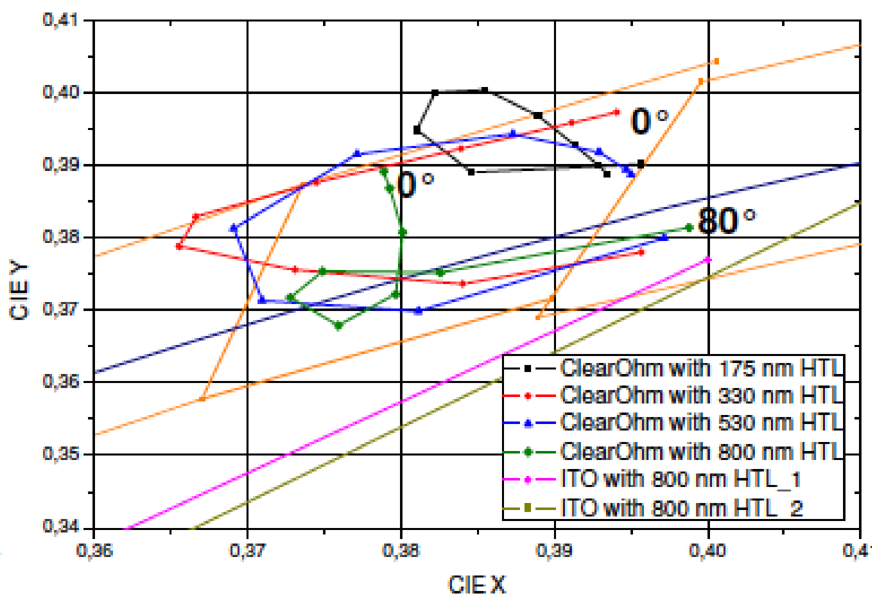


Smaller Color Shift with Angle than ITO

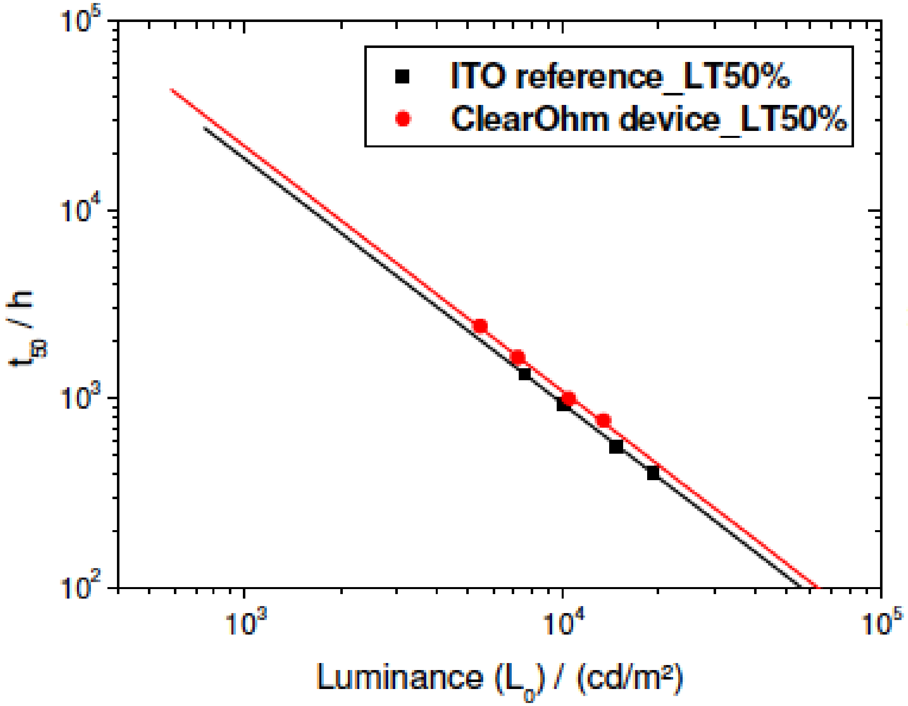
CIE 1931 angular dependance

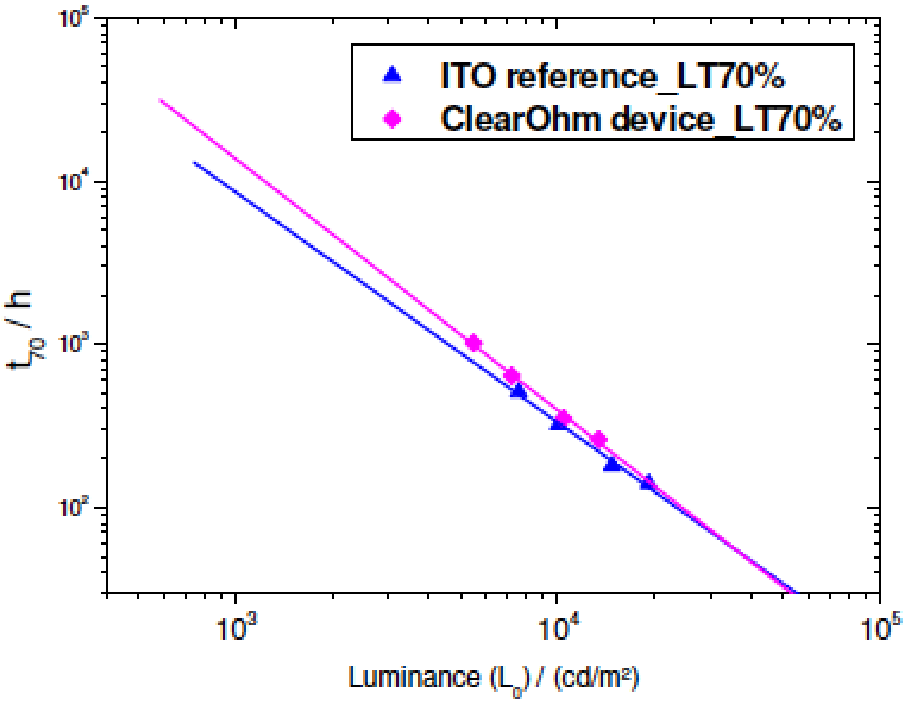
- **Color shifts in fairly smaller range for ClearOhm devices than ITO reference from 0° (normal) to 80°**
  - **Quite promising results for tandem stack**





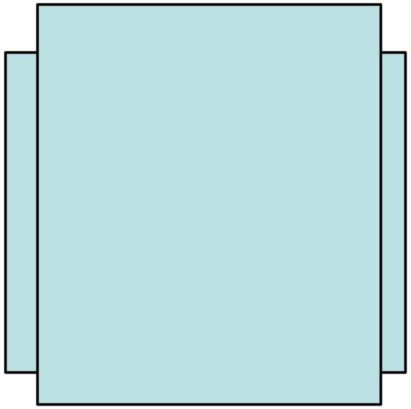
Similar Lifetime as ITO

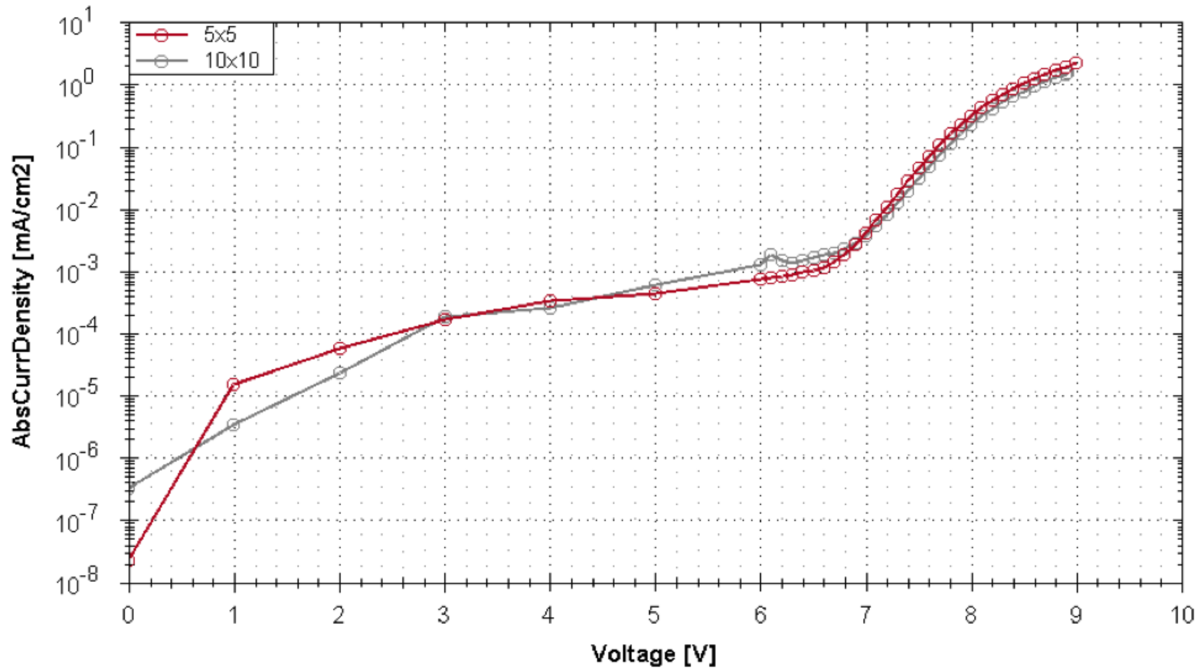




Sample	ClearOhm device				ITO reference			
Diode #	D1	D2	D3	D4	D1	D2	D3	D4
Curr. dens. (mA/cm²)	30	40	60	80	30	40	60	80
50% lifetime (h)	2425	1660	1000	770	1350	940	560	410
70% lifetime (h)	1020	640	350	260	510	320	180	140
LT50 at 1000 cd/m²	21400, [n=1.29]				18500, [n=1.30]			
LT70 at 1000 cd/m²	14100,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

>30 Lm/W 10cm x 10cm Lighting Tile





3 Unit Tandem stack

1000 Cd/m2 at 8.6V

>30 Lm/W , >40 Cd/A

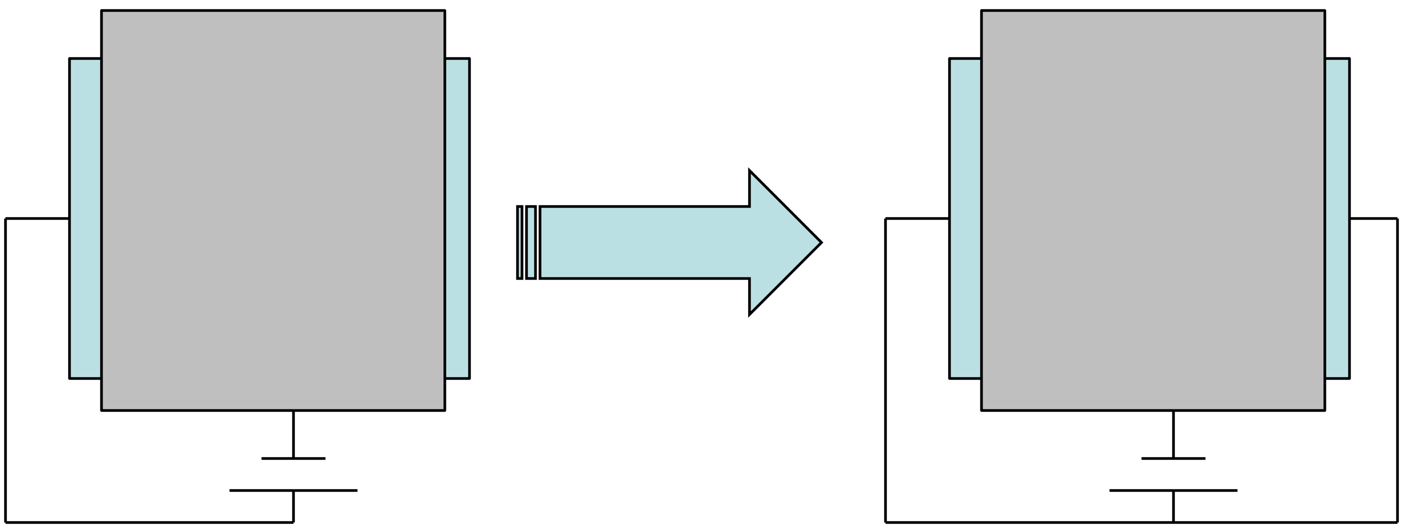
CIEx/CIEy: 0,477/0,416@1000 Cd/m2

Anode Sheet Resistance: 15 ohms/sq

Uniformity: Lmax/Lmin =2 with single sides contact

Improving Uniformity of Light Emission

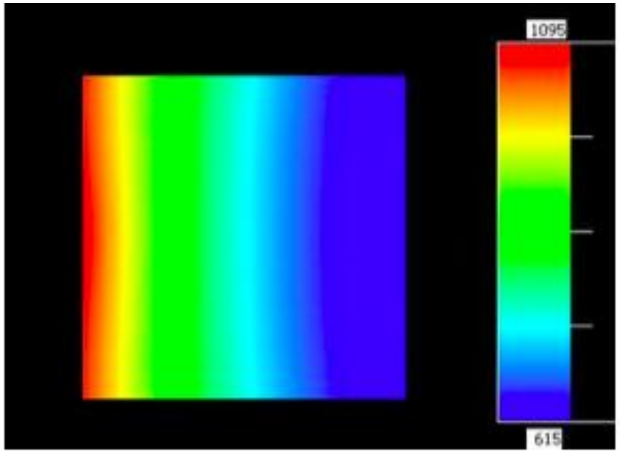
- Reduce ClearOhm Layer (Anode) sheet resistance: 15Ω/sq → 5Ω/sq
- Anode Contact on two sides or 3 sides
- Move from square to rectangular geometry:
  - 10cm x10 cm =100 cm^2 ➔ 12.5cmx8cm= 100cm^2



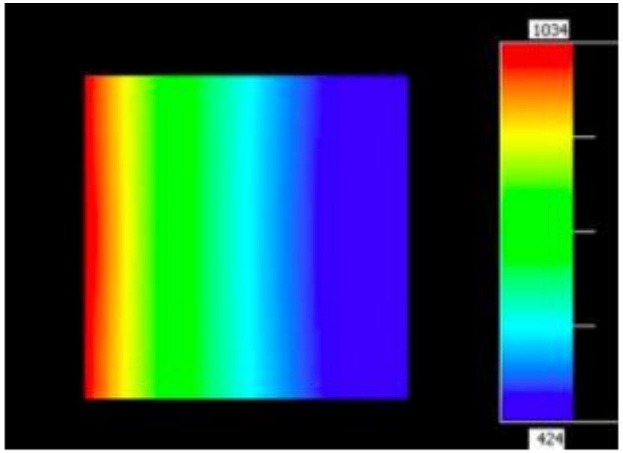
Single sided anode contact

Double sided anode contact

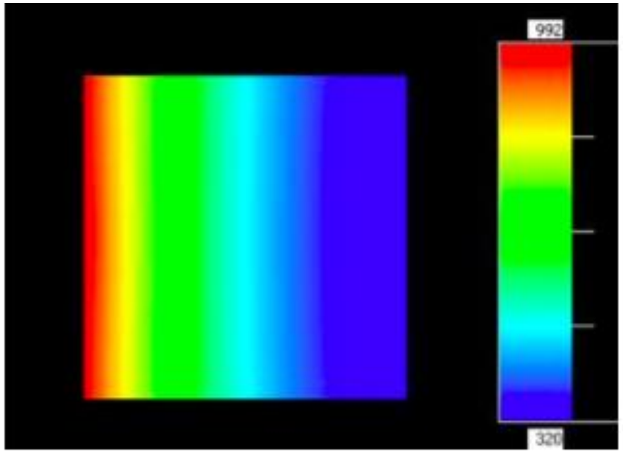
Simulation: Emission Uniformity for 10cm x10cm Tile single contact



5 Ω/sq



10 Ω/sq



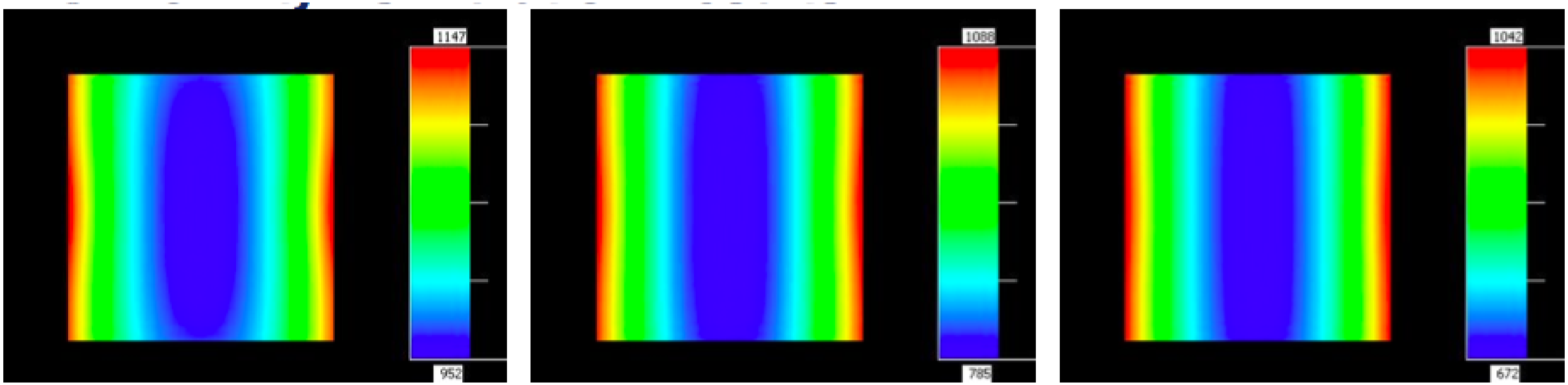
15 Ω/sq

OLED Stack	Sheet resistance of anode [Ω/sq]	Luminance [cd/m²]	Ratio of l_{max}/l_{min}	OLED voltage [V]	
3 Unit Tandem Stack	5	615 – 1095	1.78	8.00 – 8.21	
	10	424 – 1034	2.44	7.88 – 8.19	
	15	321 – 992	3.10	7.81 – 8.17	

Measured Uniformity of 10x10cm tile with 15 /sq:

Lmax/Lmin ~ 2 at 1000Cd/m^2

Simulation for 10cmx10cm Tile: Expected Lmax/Lmin < 1.2 5Ω/sq, Double Sided Contact



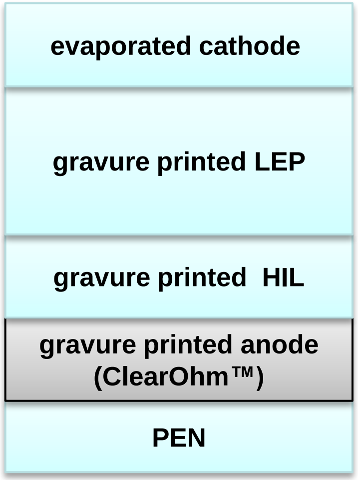
5 Ω/sq **10 Ω/sq** **15 Ω/sq**

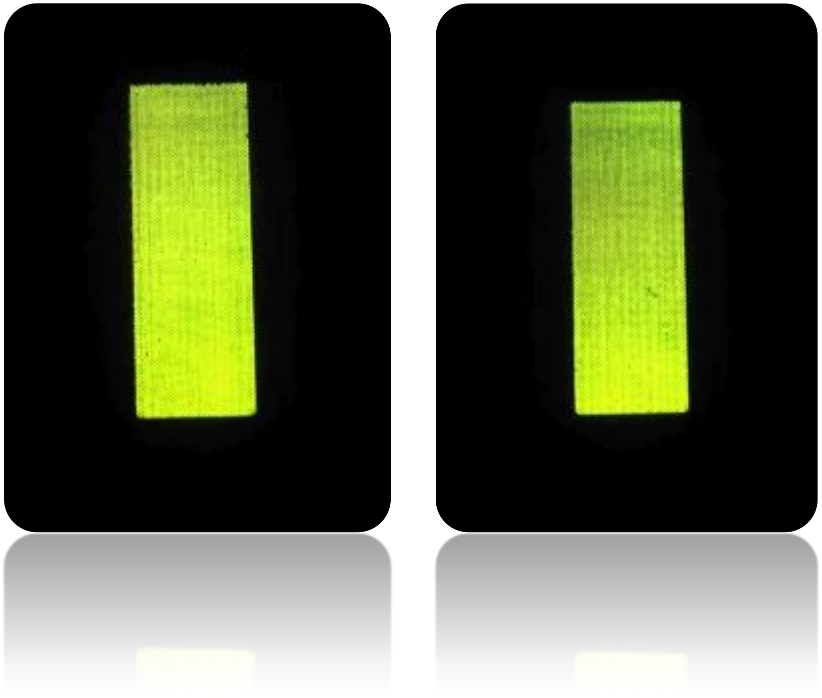
OLED Stack	Sheet resistance of anode [Ω/sq]	Luminance [cd/m²]	Ratio of l_{max}/l_{min}	OLED voltage [V]	
3 Unit Tandem Stack	5	951 – 1147	1.20	8.16 – 8.23	
	10	785 – 1088	1.38	8.09 – 8.21	
	15	671 – 1041	1.55	8.03 – 8.20	

Uniform 10x10 cm OLED Lighting Tiles can be made with ClearOhm Anodes

Gravure Printed OLED

- OLEDs with 3 gravure printed layers processed at VTT: Anode, HIL and LEP





ClearOhm™ Ink printing direction

HIL, LEP printing direction

55

Thank You

www.cambrios.com

rgupta@cambrios.com

+1 408 239 9772