The Role of Hole Injection Layer in Enabling OLED Device Performance and Defect Tolerant Manufacturing

June 7th, 2011

"OLED Materials for Lighting and Displays"

A New Industrial Chemistry and Engineering (NIChE) Workshop by the Council for Chemical Research

Plextronics Overview

PLEXTRONICS
Light. Power. Circuitry.™

Key Facts:

- Founded in 2002
- Based in Pittsburgh, PA USA
- Approximately 70 employees
- 190+ individual & pending patents worldwide
- Strategic investors: SOLVAY; Applied Ventures, LLC – APPLIED MATERIALS

Business Model:

Develop and manufacture high-performance inks & leading-edge device technology for printed electronics

Core Capabilities:

- Conductive polymer design and manufacturing
- Ink formulation, coating, and printing
- Printed device design & engineering

Dedication to Quality

ISO 9001 certified
ISO 14001 compliant

ANAB ACCREDITED
ISO 9001:2008 No. 43632

Target Markets:

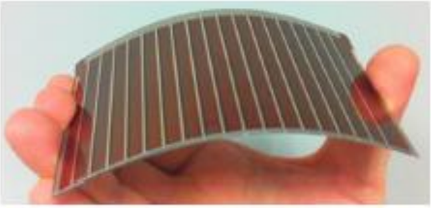
*W-OLED = "White OLED" for lighting applications

Existing Product Lines:

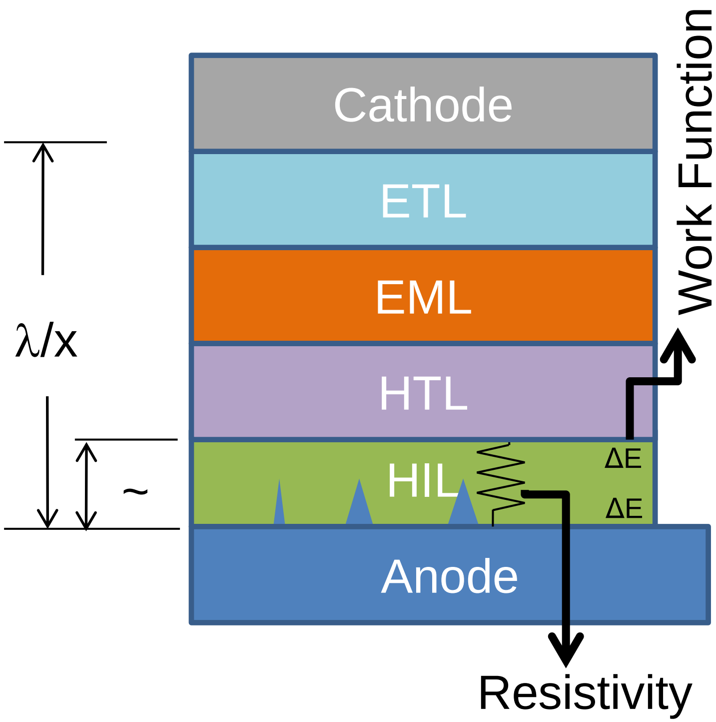
- *Plexcore® OC:* Conductive polymer inks for Hole Injection Layer (HIL) formation in OLED lighting and displays
- *Plexcore® PV:* OPV ink systems including matched Photoactive (p/n) and Hole Transport Layer (HTL) materials
- *Plexcore® OS:* P3HT polymer for OPV and OFETs

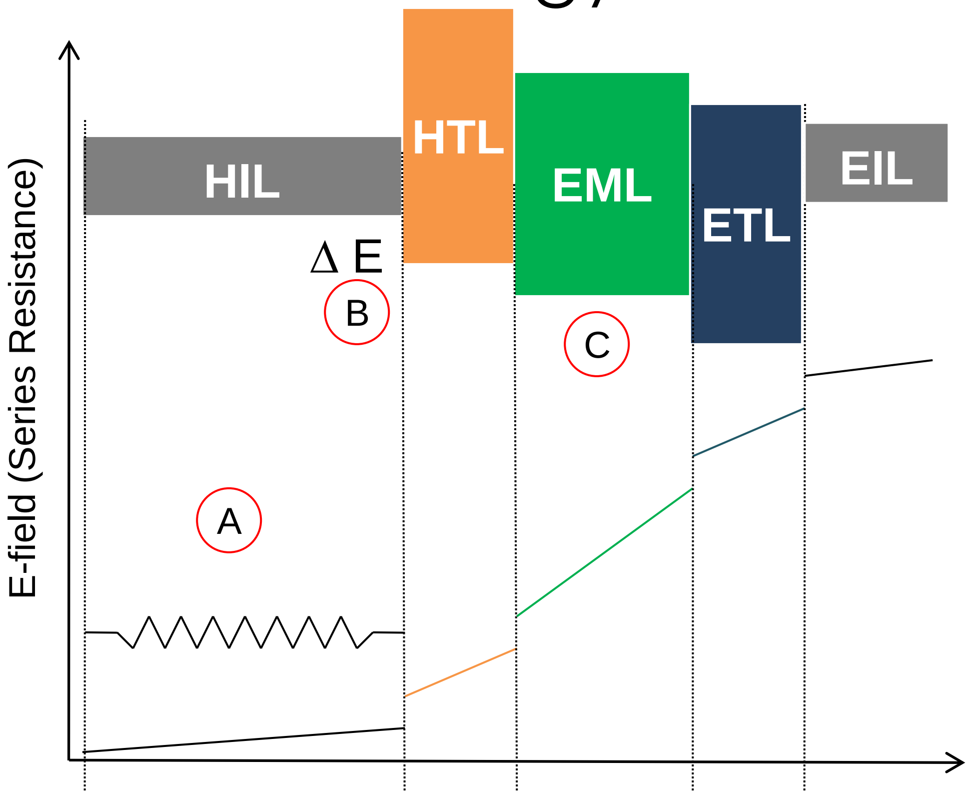
New Product Lines:

- *Plexcore® HIL/HTL:* Ink system for printed OLED lighting and displays
- *OPV Device Licensing:* Printed solar devices incorporating Plexcore® PV inks specially designed for use with indoor, artificial lighting



Role of State of the Art Wet-Processed HIL Technology





- Minimize energy barriers at anode and HTL interfaces
- Minimize voltage penalty as a f(thickness)
- Facilitate freedom in optical cavity design
- Passivation of defects on electrode surface

Outline

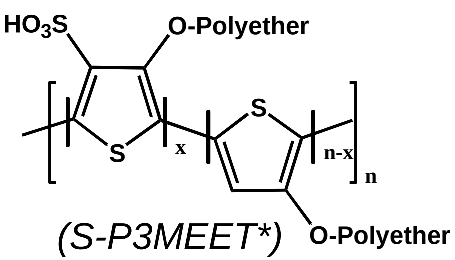
- Overview of Plexcore OC Technology
- High performance OLED stacks using Plexcore OC
  - Display
  - Lighting
- 150 x 150 mm coating capability at Plexcore OC

Plexcore OC Product Lines

Combining conducting polymer chemistry
with ink formulation & processing expertise

Inherently-Doped Conductive Polymer	+	Additives: • Matrix Polymer • Surfactants • Optional Dopants • Additives	+	Choice of Co-solvents

Plexcore OC AQ



(S-P3MEET*)

- ✓ Aqueous-based HIL for various printing methods (IJP, slot die, nozzle)
- ✓ Commercially Available
- ✓ Designed for P-OLED and hybrid phosphorescent stacks

Plexcore OC NQ

Proprietary
Conductive polymer

- ✓ Solvent-based HIL
- ✓ Spin-coat samples available
- ✓ Compatible with all-solution phosphorescent OLED stacks

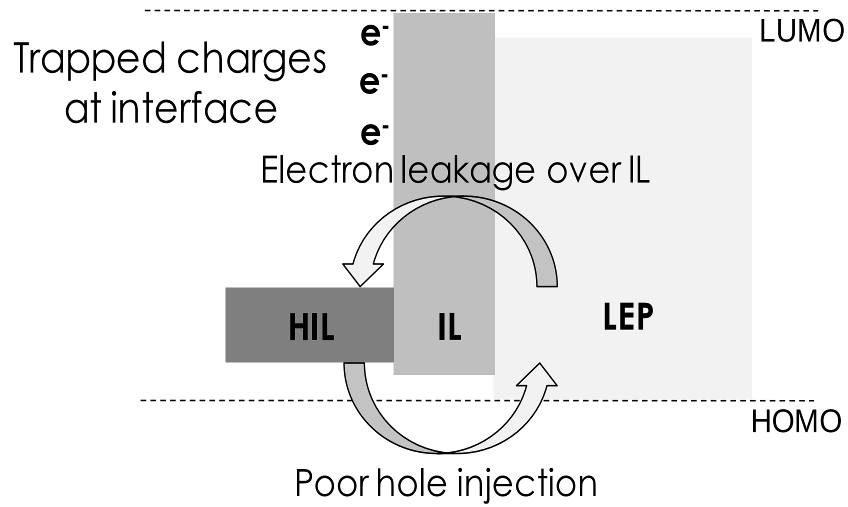
Plexcore OC HTL

Proprietary
Crosslinkable Material

- ✓ Solution-processable HTL
- ✓ Under Development
- ✓ Enables all-solution phosphorescent stacks

** Sulfonated poly(thiophene-3-[2-(2-methoxyethoxy)ethoxy]-2,5-diyl) (S-P3MEET)*

Plexcore® OC is Resistant to De-doping Phenomena



see also de Kok, M. M. et al *Physics of Organic Semiconductors*, Wiley-VCH, Edt. Brutting, W., 451-470

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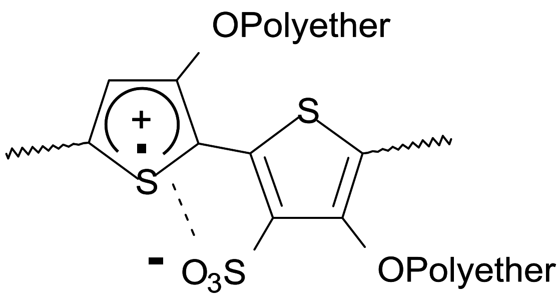

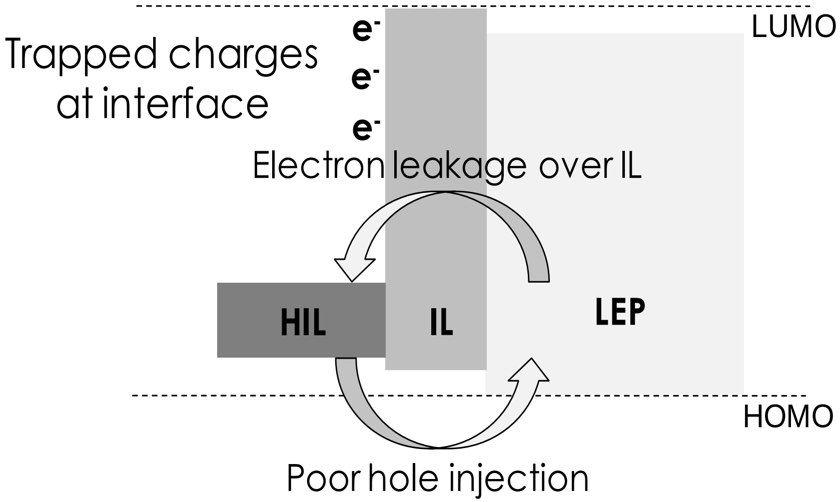

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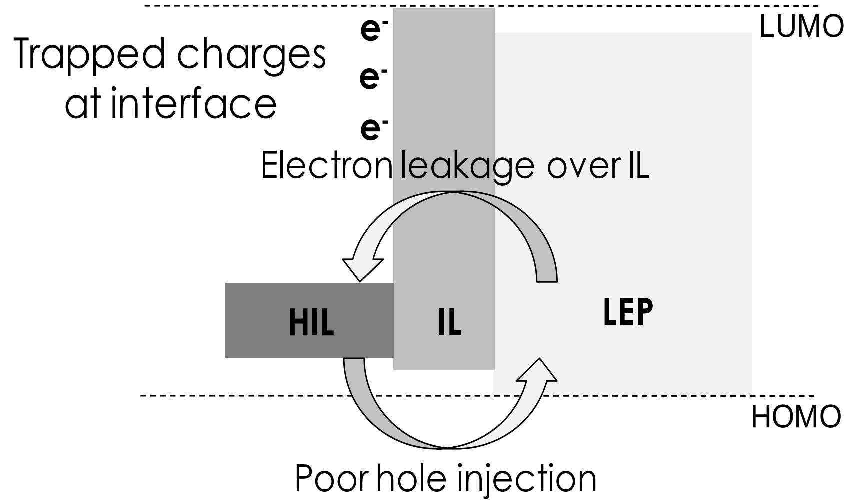
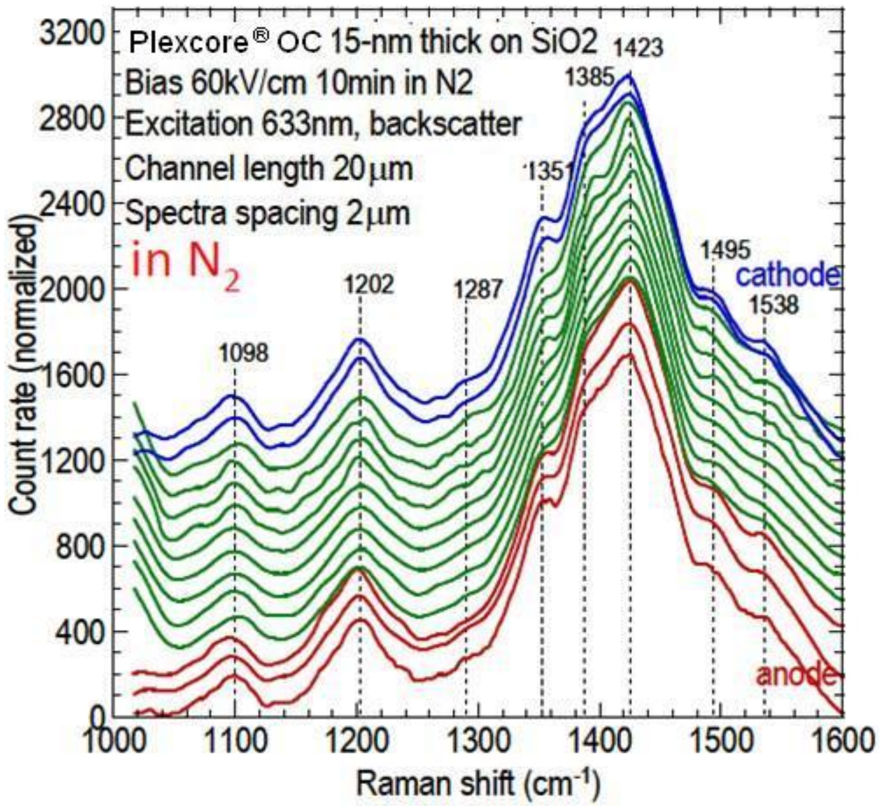


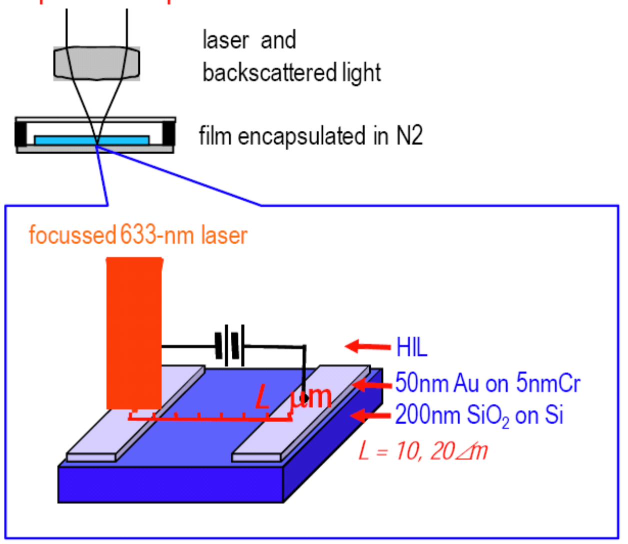
Exposure to electron current for some aqueous solution processed HIL/HTL materials can lead to operational performance degradation via dedoping phenomena

see also de Kok, M. M. et al *Physics of Organic Semiconductors*, Wiley-VCH, Edt. Brutting, W., 451-470

Micro-Raman Supports Absence of Dedoping



Experiment protocol

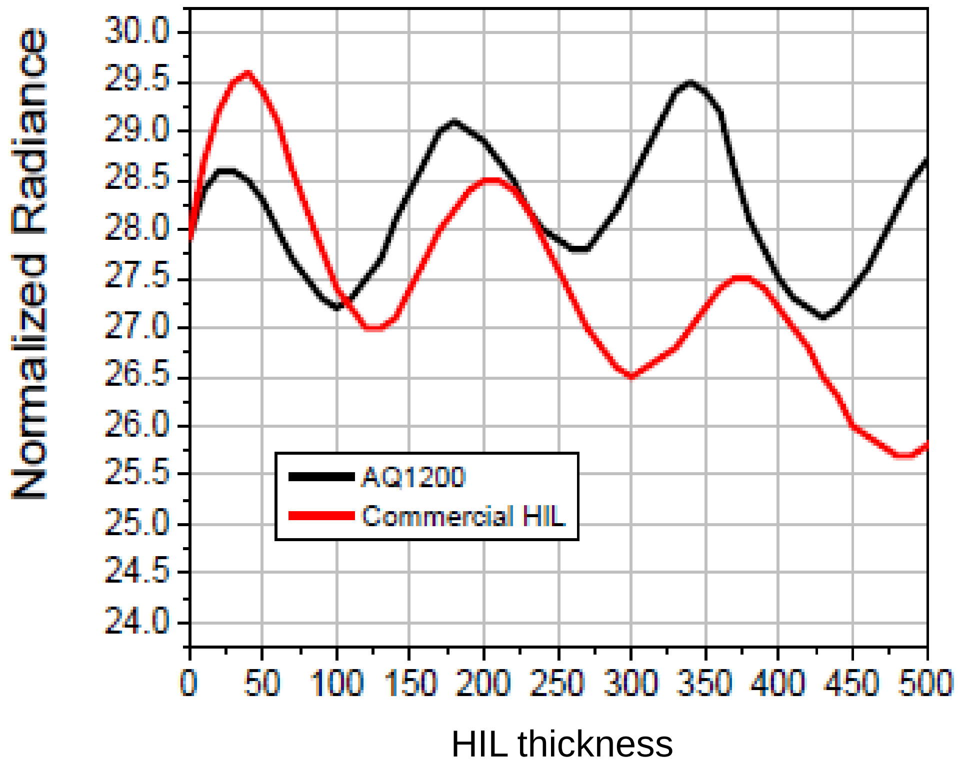


Measured on InVia Renishaw Raman microscope with HeNe 633nm laser focussed through a x20 (NA0.75) objective and at a power that does not cause laser-induced damage as verified by repeated measurements at the same spot. All samples were encapsulated in N2 before Raman measurements to prevent photo-oxidation during measurement. No bias was applied during measurement.

In N_2 and air up to 60 kV (120V), there is no evidence of electrically-induced change in the doping-level of Plexcore® OC

see also, Ho, P. K-H. *Adv. Materials* 2007, 19, 4202

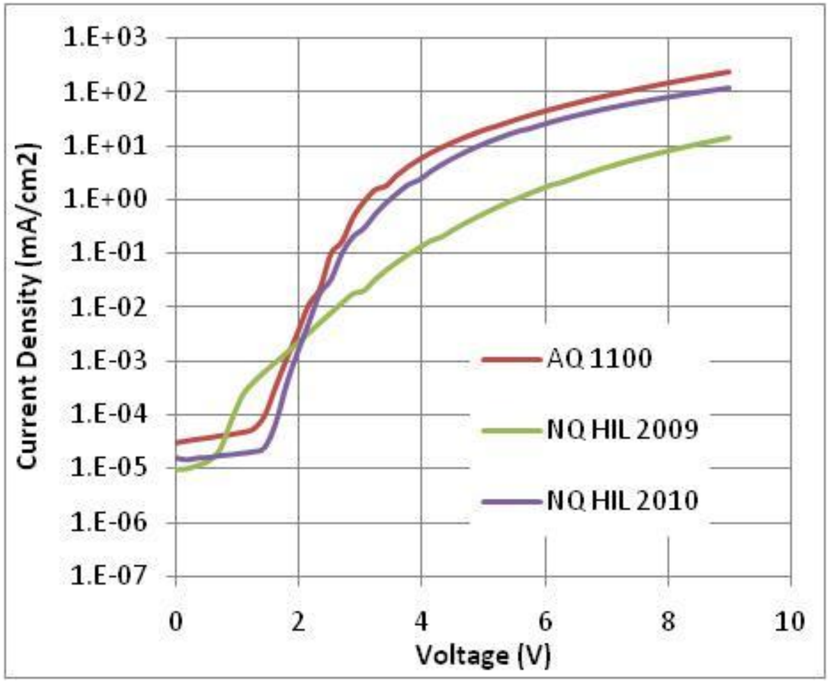
Using AQ HIL for Optical Cavity Tuning



- Simulation results show higher light out-coupling at higher HIL thickness
- Potential to further increase the allowed thickness to facilitate planarization

New Development: Improving Hole Injection Capability of Non-Aqueous HIL

Hole Only Device: ITO/HIL/NPB/Au



Design Rules
No protons → No water or protic solvents
High Transparency
Planarization

Performance Benefits:

- Eliminate degradation mechanisms
- Enable higher performing phosphorescent devices

New Non-Aqueous HIL delivers comparable hole injection to Aqueous HIL

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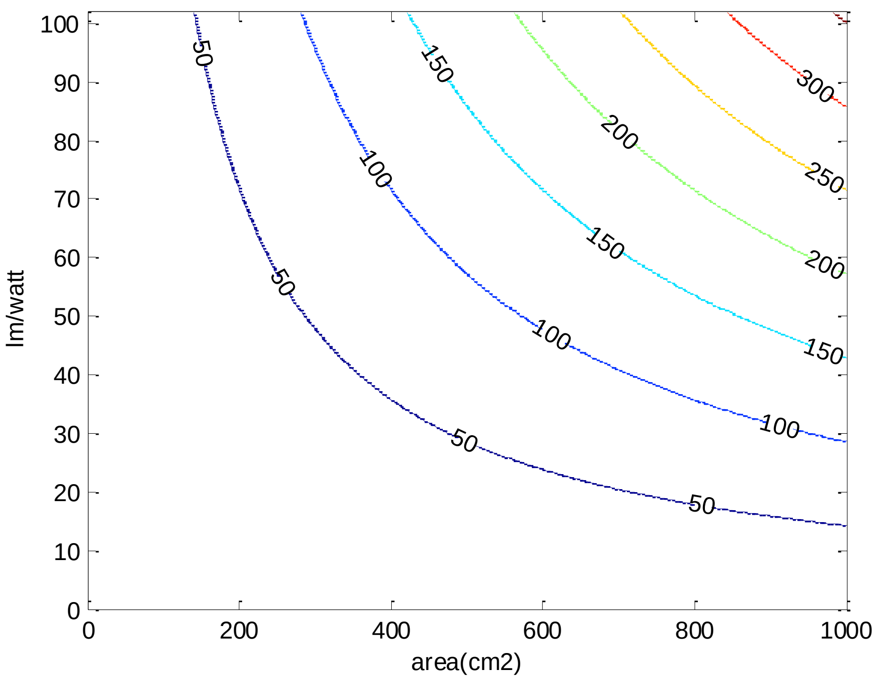
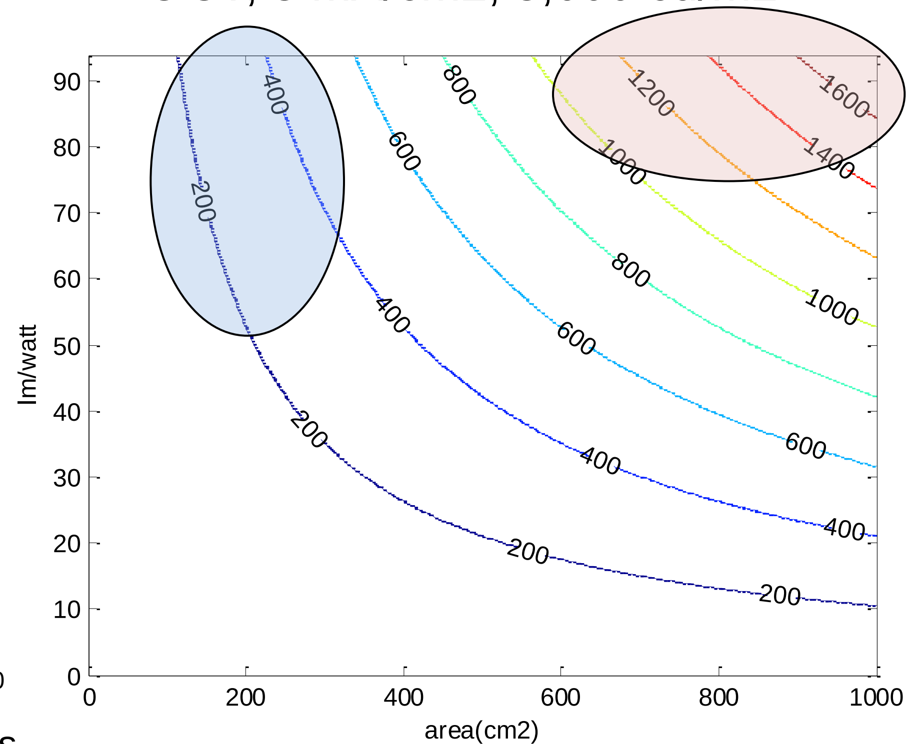
HIL For Lighting

Lumen Output and Light Emitting Area

3.5V, 1 mA/cm2, 1,000 cd/m2



3.8V, 5 mA/cm2, 5,000 cd/m2

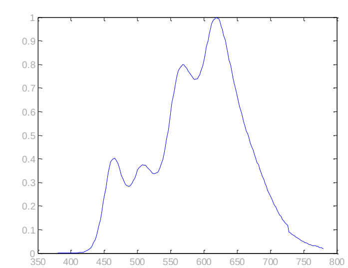


Assumptions-

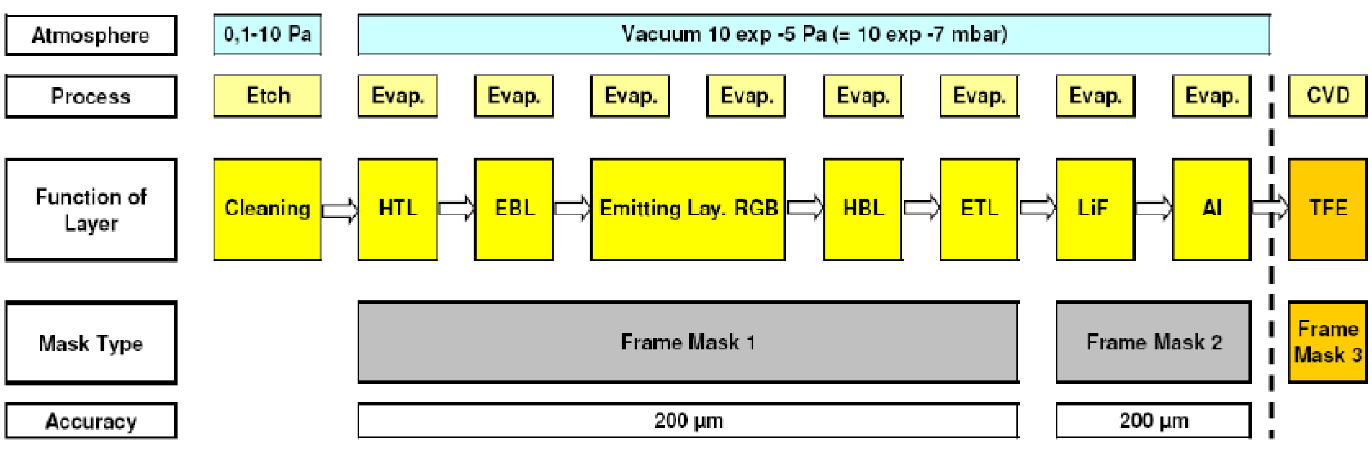
- 80% IQE, 70% Light out-coupling
- Lambertian emission

EL spectrum used in simulation corresponds to Illuminant A (Incandescent bulb)

- At a brightness of 1,000 cd/m2 lumen output is limited
- At 3,000 to 5,000 cd/m2 lumen output enables different applications for reasonable dimensions of panels
- There are two areas a) operating voltage to maximize light output and b) practical limit of production panel area where HIL can play a role



OLED Manufacturing Processes

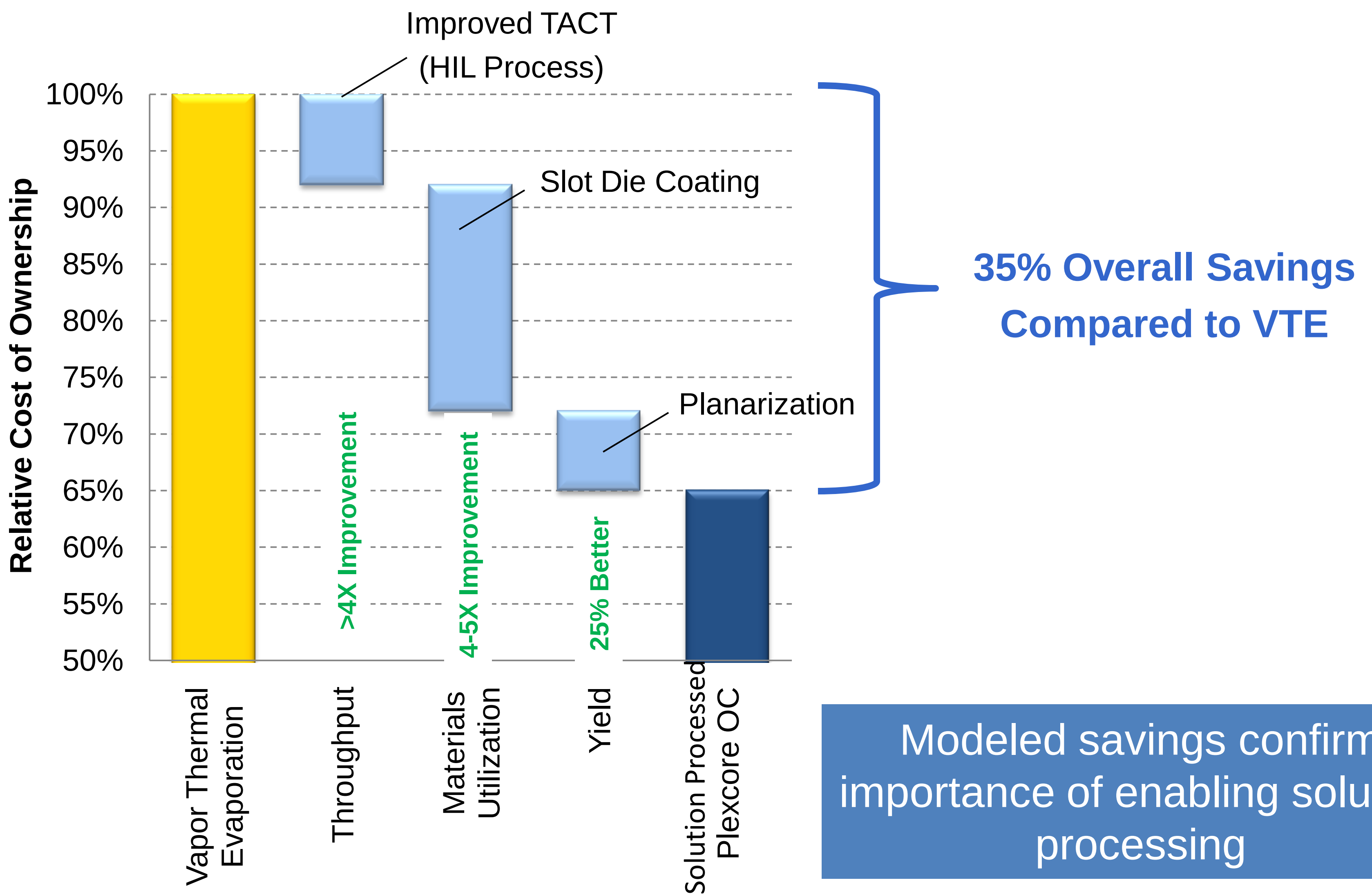


Example of OLED Fab line, Applied Materials

- Pilot lines with select device architectures, materials sets and equipment are being set up
- Opportunity exists to lower costs of panels via demonstration of improvement in specific unit operations
  - Demonstrate better materials utilization
  - Lower cycle time
  - Demonstrate improved yield

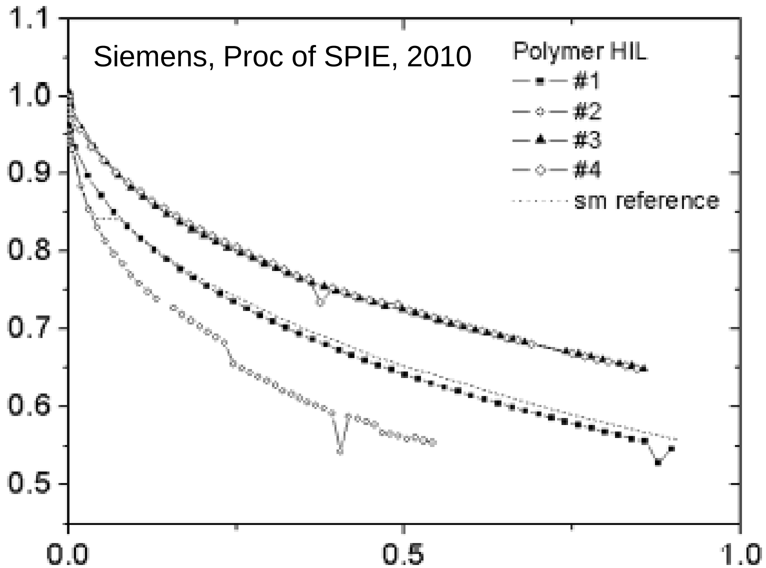
Why focus on HIL?

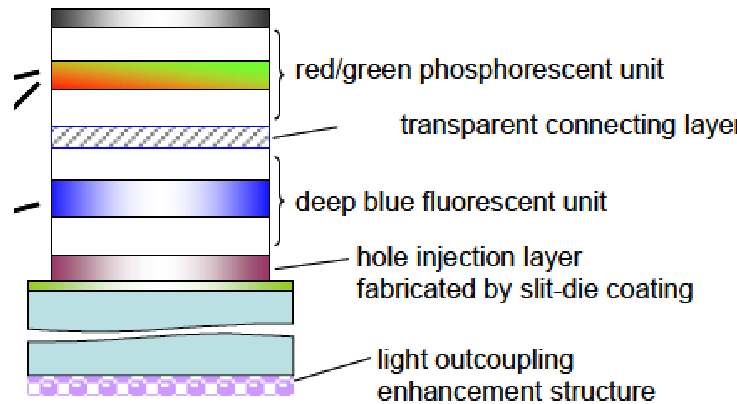
Case Study: Model replacement of one VTE process step



Modeled savings confirm importance of enabling solution processing

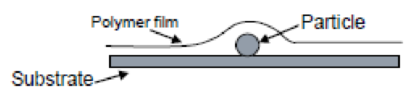
Use of p-doped Hole Injection Layer (HIL) in OLED SSL Device Stacks





Panasonic, SID 2011

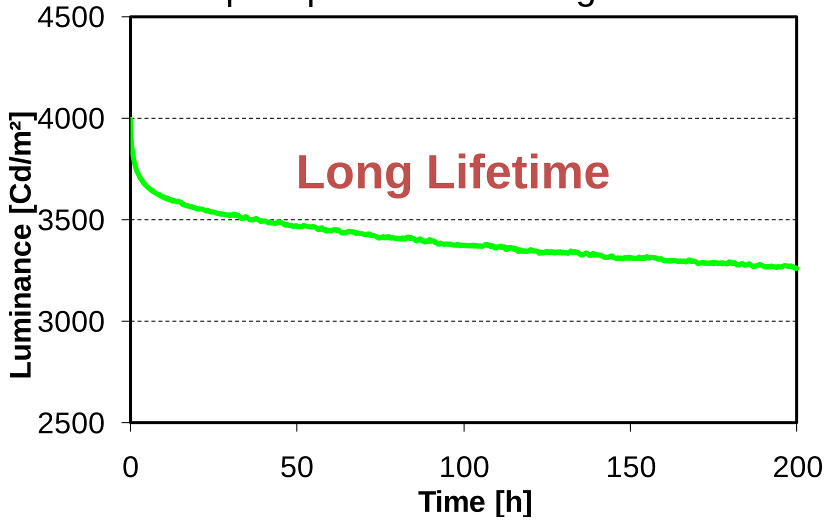
Layer combinations	RMS [nm]	R_a [nm]
ITO	1.452	1.162
ITO / #1	0.758	0.604
ITO / #1 / evap. IL / NPB	0.829	0.658
ITO / evap. IL / NPB	1.907	1.512

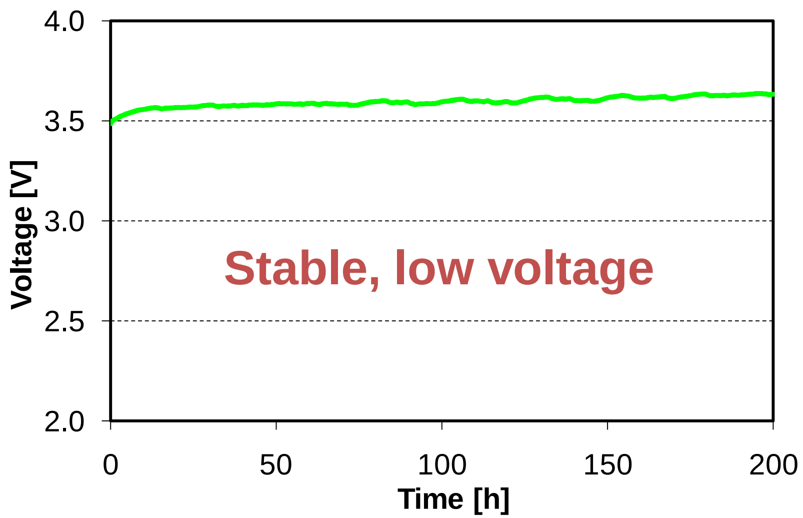


- High performance ‘hybrid devices’ that incorporate solution based HIL and vapor organic layers are becoming more common
- The use of solution based HIL offers added advantages for manufacturing that go beyond device stack development for efficacy and lifetime

Long lifetime and low voltage in Hybrid phosphorescent SMOLED Device

ITO/Plexcore OC/Ir (phq)
VTE phosphorescent orange emitter





Performance Metric	Value
Voltage	3.1 V
EQE	7.3
Cd/A	12.9 Cd/A
Lm/W	12.9
Lifetime (T75, 4000 nits)	1,145 hrs
Lifetime (T50, 1000 nits)	**107,000 hrs***

Solution processed Plexcore OC in a vapor deposited stack exhibits excellent lifetime coupled with voltage stability

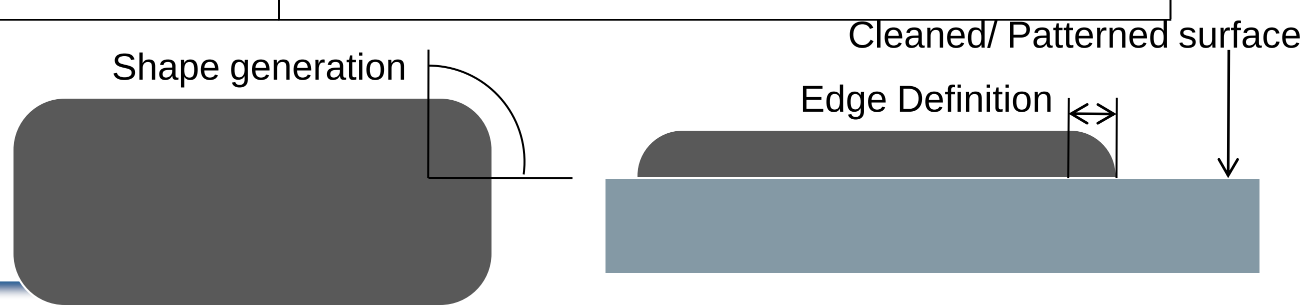
Yield Improvement is driver for Large-Area Manufacturing

Guidance for Materials Development-Device

Variable	Description
Interface energy offsets	Achievement of a flat band device architecture with attention paid to processes that create the final interface
Mobility within OLED device layers	Maximizing mobility helps in bringing down voltage once interfaces are dealt with. This can also facilitate increasing the thickness of the layers. Materials design that facilitate improved charge transport (sensitive to deposition process variables for wet processing) is key here.
Impact of Charge Trapping and Interfaces on lifetime	Materials need to be designed to be robust to charge trapping phenomena which are an essential element of mechanism for light emission in the emissive layer. Design of architectures should facilitate minimization of charge accumulation at interfaces. Simpler device architectures minimize the number of interfaces but are also susceptible to more charge trapping

Process Development- Organic Layer Deposition

Work Package	Package Classification	Tasks to Monitor
Process development for thin film deposition	Processability- Air/Dry Air/Inert	Environment for coating and for drying
	Tool + Ink evaluation	Coating speed, thickness uniformity, process package for production environment, duration of operation/uptime in coating trial
	Film coating evaluation	Film uniformity, wetting on backplane features
	Patterned deposition	Tolerance for film edge alignment with backplane features
	Film drying	Drying method, number of ovens, environment, anneal time, solvent stripping
	Time/Environment between coating steps	Substrate handling requirements, variation & tolerance to variation in queue time windows, ability to store film coated substrates



Materials & Translation to Panels

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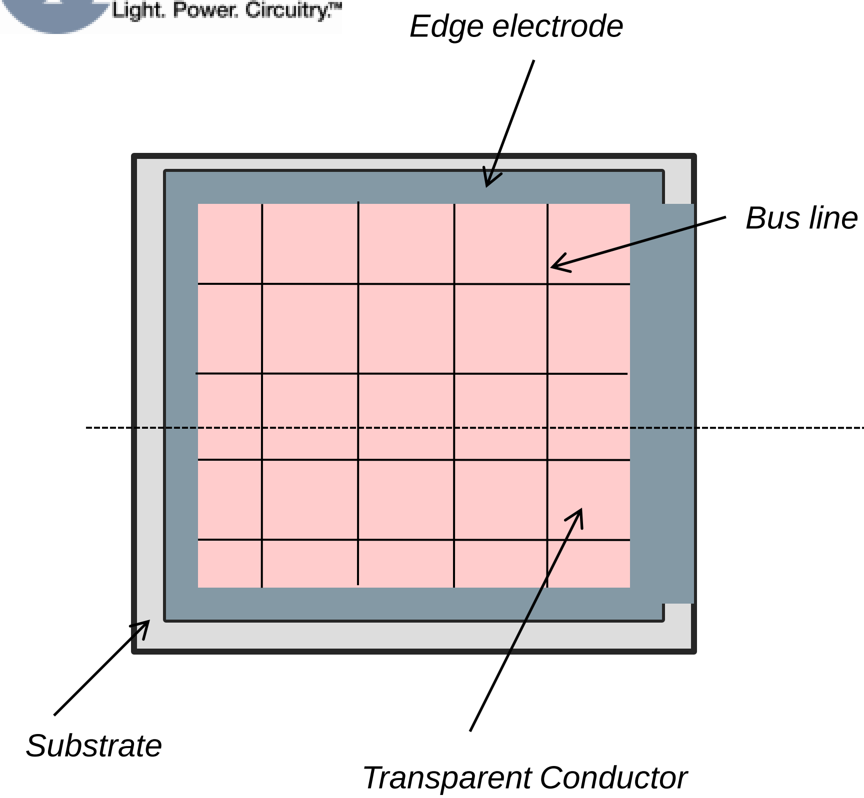
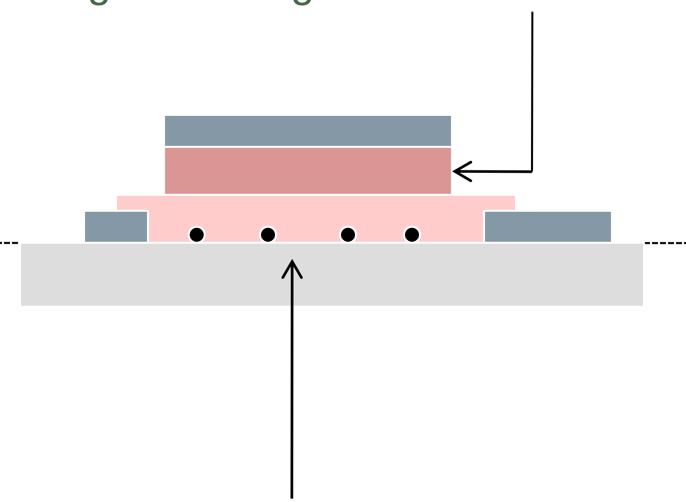


Materials & Device Architecture Development to increase current at given voltage



Deposition of layers
- Multiple surface types exist during coating events
- Thin film coatings need to maximize materials usage
- Solvent selection to facilitate fast drying times

Need to improve thermal management for higher current
- Reduce non uniform degradation due to thermal effects
- Reduce pathways for leakage current
- Address tradeoff between the illuminated area of the panel and thermal management strategies such as bus lines

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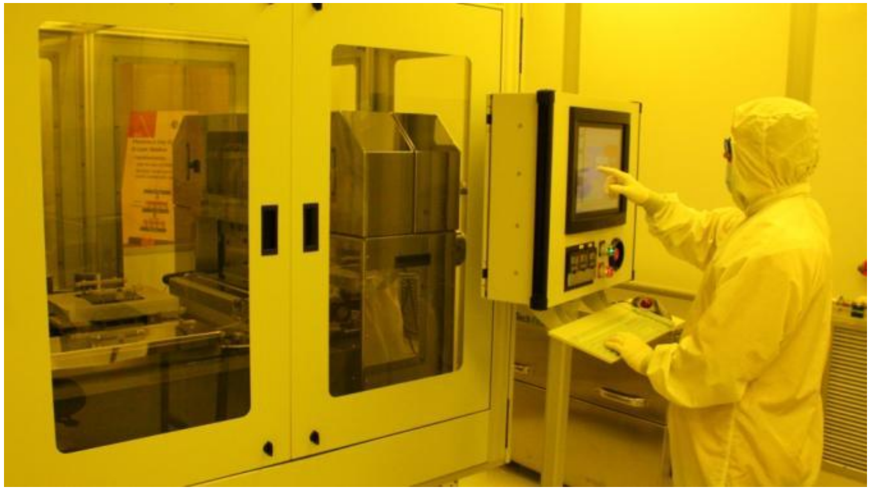
Guidance for Materials Development-Panel

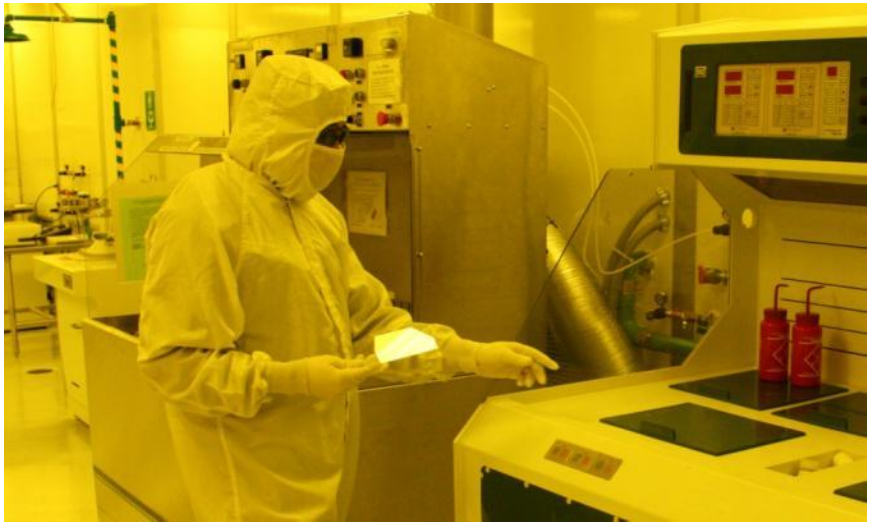
Variable	Description
Sensitivity of materials to handling environment	Ability to improve process throughput is key. This is defined on the basis of a) robustness to moisture/oxygen/light b) solvent removal conditions for wet processed layers c) base purity of materials and solvents
Device performance tolerance to thickness uniformity over large areas	Scaling materials demonstrated to perform in lab devices to large are substrates requires the use of deposition techniques that will not easily lend themselves to maintaining thickness uniformity for 10nm films. Hence demonstration of low sensitivity of operating voltage to layer thickness is essential
Scalability of material synthetic procedures	Minimize number of synthetic steps. Ensure robustness of procedure to factors that compromise purity
Thermal Effects	Materials and processes that eliminate volatiles are essential. Low cost solutions to manage thermal non-uniformities are key. Minimization of ohmic losses via selection of materials and panel design will help facilitate minimization of non uniformities in device degradation

Leveraging Available US-based Assets for Ink & Process Development

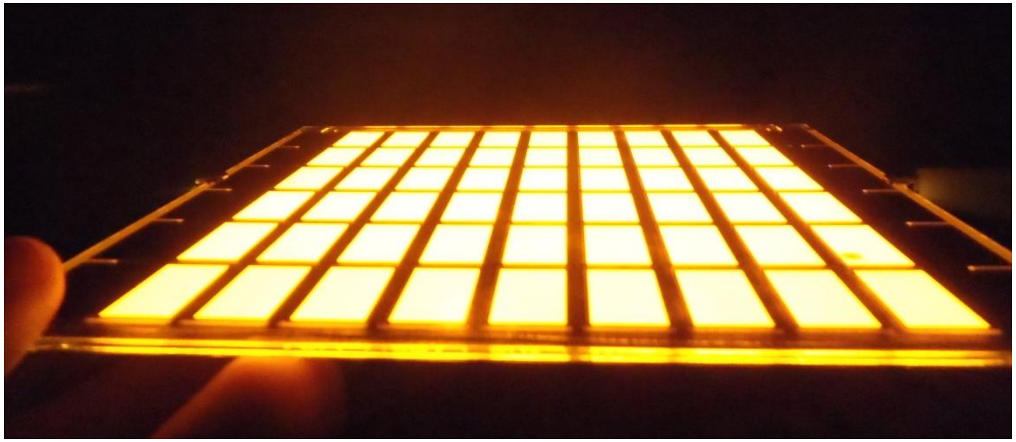
- We utilize the D-Line to evaluate our materials using manufacturing-worthy processes and equipment.

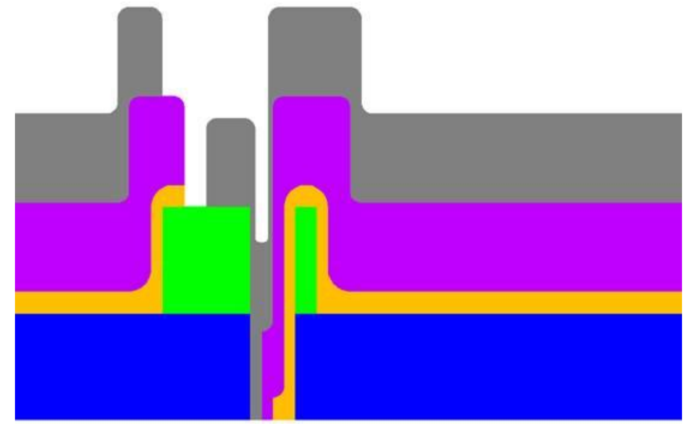
- Specifically, we are:
  - Developing inks for large area blanket coating
  - Evaluating encapsulation technologies to understand interactions within the device
  - Testing alternative cathode and device architectures
  - Implementing new module designs

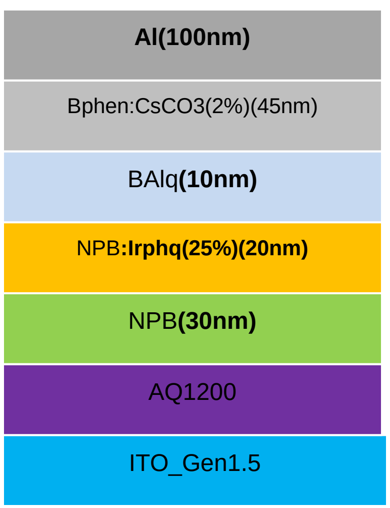




Panel Design Capability at Plextronics







- 6”X6” Orange PHOLED panel fabricated at R&D line
- Uses a 9s6p substrate design
- Uses Plexcore AQ 1200 and orange vapor PHOLED
- HIL in this case was spin coated

Summary

- ✓ Plexcore® OC is a High-Performing HIL with excellent stability to dedoping phenomena
- ✓ Low cost, scaled solution processing is key to OLED commercialization
- ✓ Tunability of HIL can modulate charge injection to optimize device stack performance
- ✓ Proven device performance with Plexcore® OC has been demonstrated across emitter platforms and technologies; shows potential for dramatic reduction in cost-of-ownership compared to vapor thermal evaporation

Thank You

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Ink Sales/Info: Mary Boone, mboone@plextronics.com
R&D volumes of select products also available through:
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