Functional Glasses: Properties and Applications for Energy & Information

Glass • Coatings • Paint

Integrated Glass Substrates for OLED Lighting

Mehran Arbab

PPG Industries, Inc.

PPG is…

PPG IdeaScapes
Glass • Coatings • Paint

- A global materials producer with 12 strategic business units in 5 major product areas:
  - **Industrial Coatings**
  - **Performance Coatings**
  - **Decorative Coatings**
  - **Optical & Specialty Materials**
  - **Glass & Fiber Glass**
- Founded in 1883, Headquartered in Pittsburgh, Pa.
- More than 40,000 employees, 150^+ manufacturing sites, in 60^+ countries
- Invests 3% of revenue in research and development

Our Planet at Night

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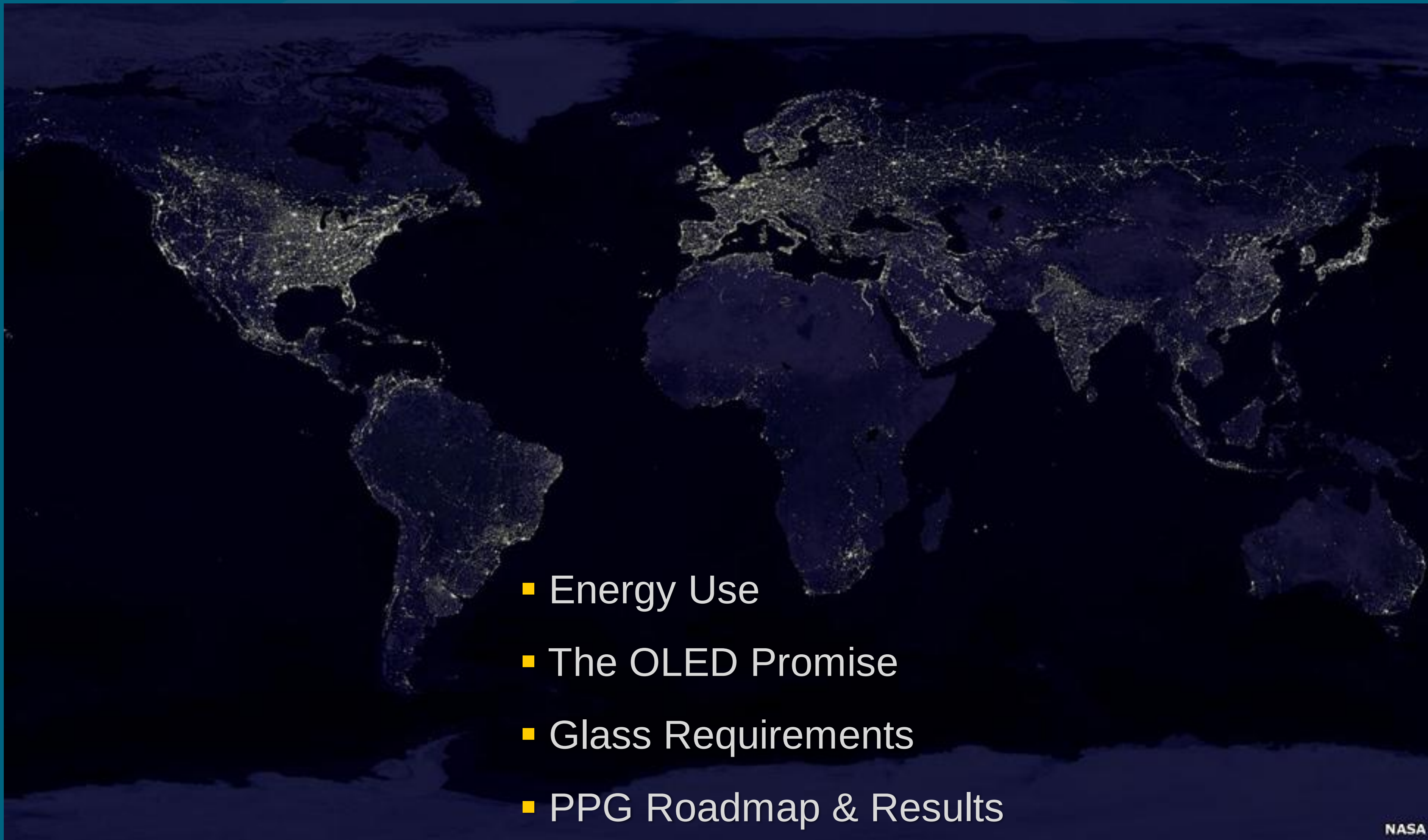


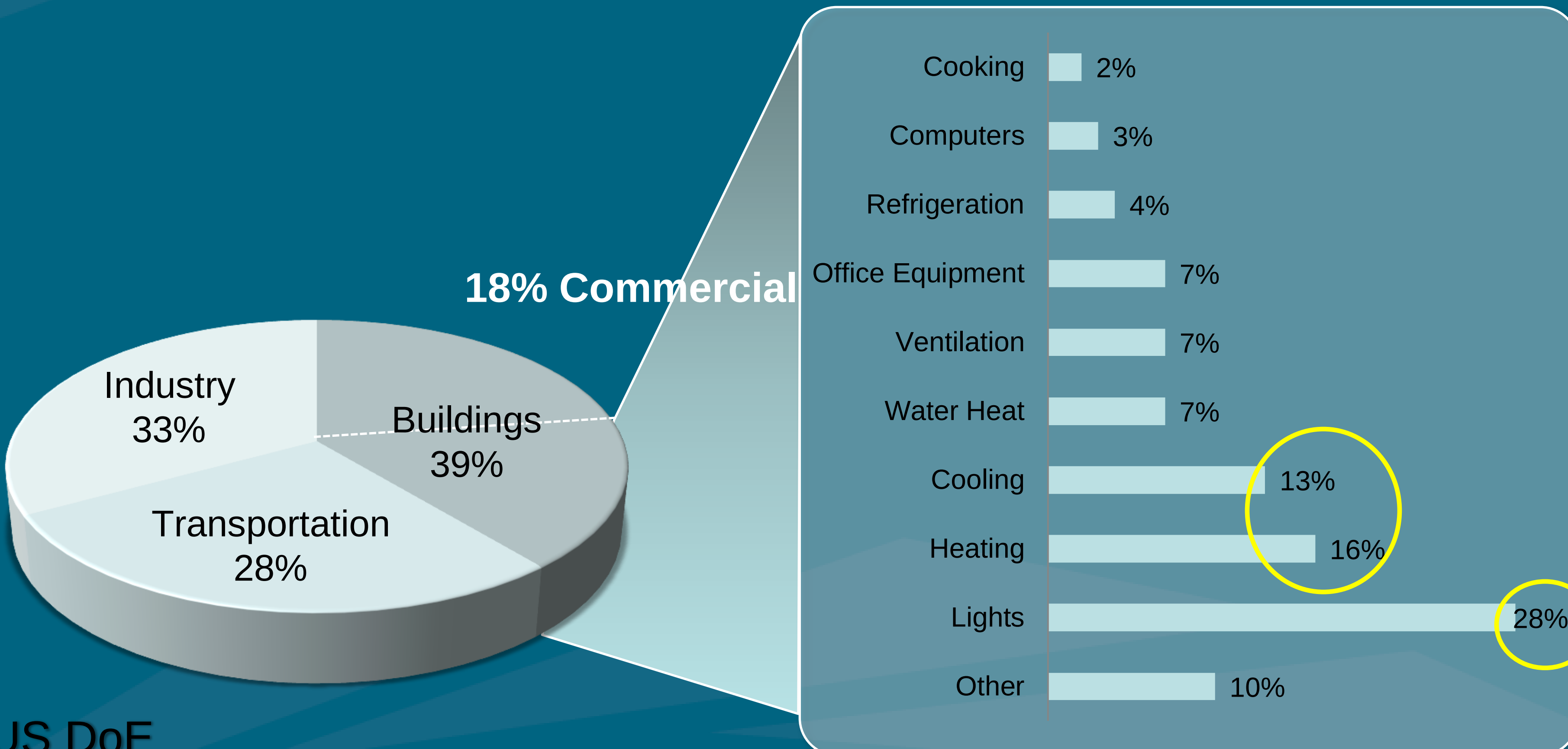
- Energy Use
- The OLED Promise
- Glass Requirements
- PPG Roadmap & Results

Beautifully bright, wasteful and uneven

Building Energy Demand Challenge:

End-Use Energy Consumption

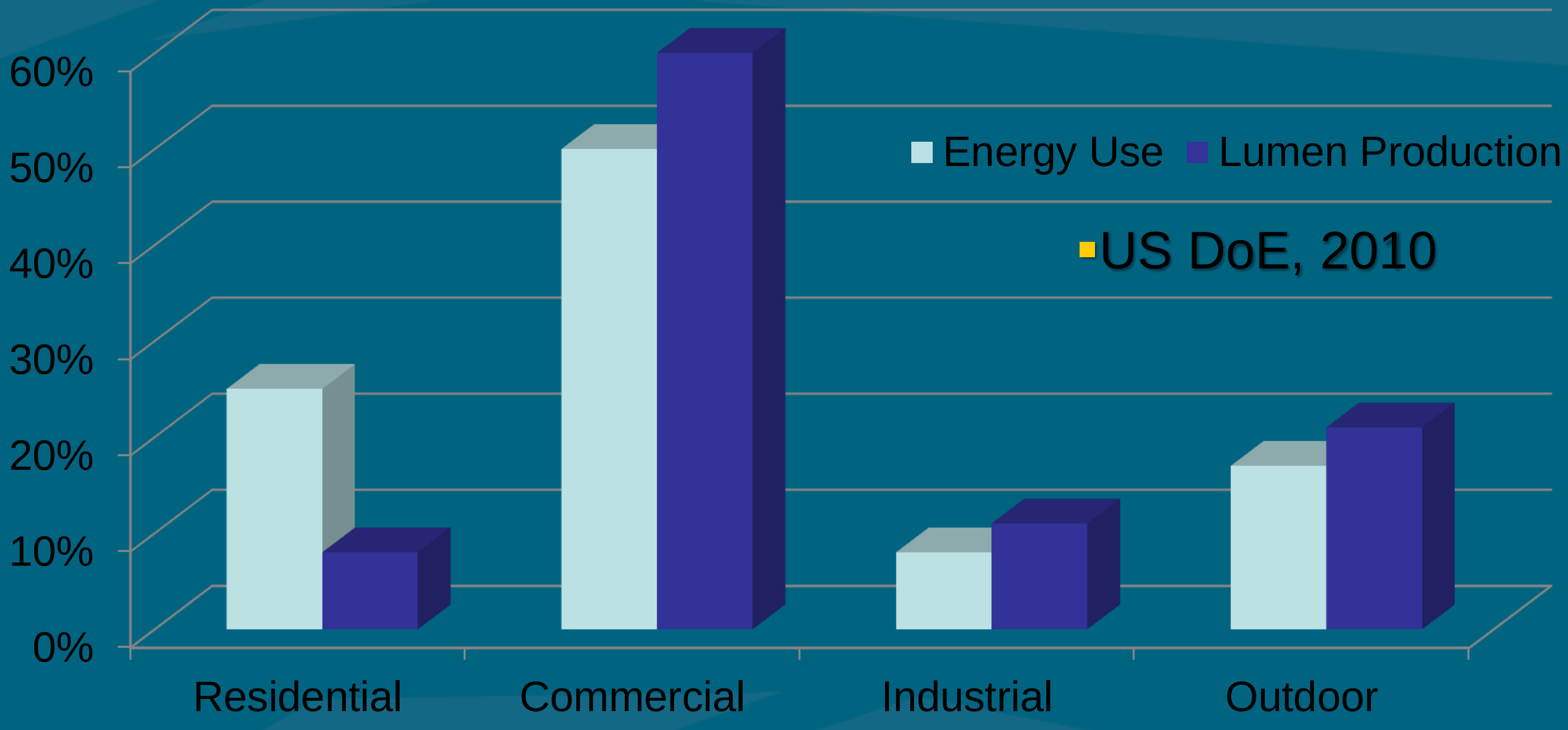
- Buildings consume 39% of total U.S. energy
  - 71% of electricity and 54% of natural gas



US DoE

Lighting in the United States

>250 GW.yr of Primary Energy ⇒ 80 GW.yr of Site Energy



Room for improvement with exiting technology

Lighting Technology is Evolving

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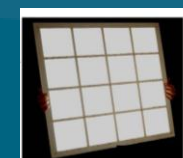
Incandescent Bulb

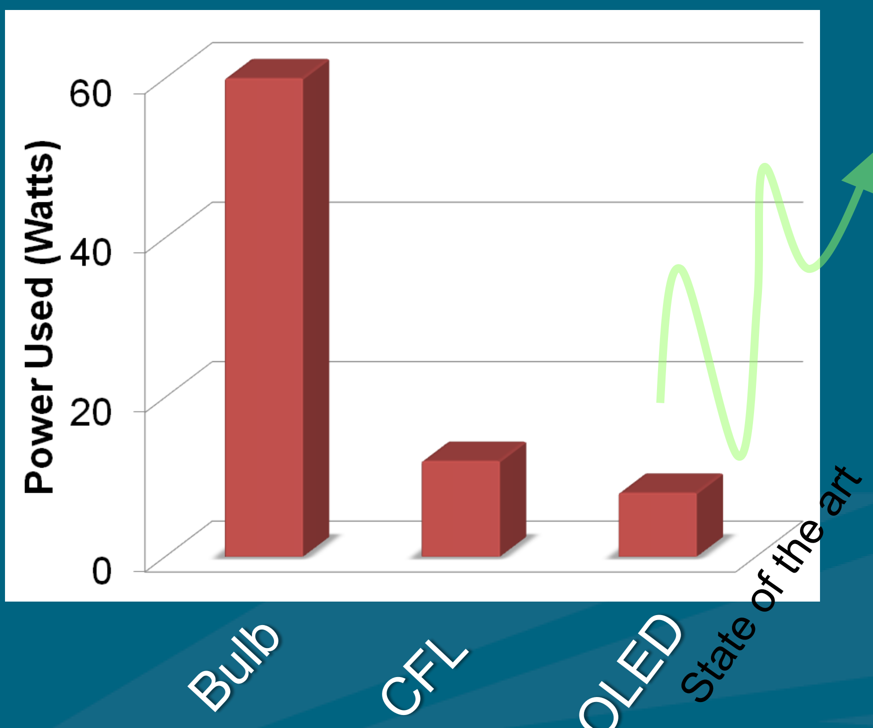
Low Efficiency
Short Lifetime

Compact Fluorescent Lamp

Environmental Problems
Poor CRI

Solid State Lighting





Low environmental footprint, Design-friendly

Warm white light, High Color Rendering Index

Large area processing

Still costly, in early Manufacturing and commercial stages

Transformational Ideas

Electroluminescent Molecules

Technology	Price (USD)
Fluorescent Luminaire	~500
OLED Luminaire	**~10,000**

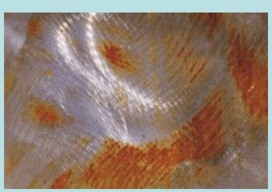
Lighting industry

Legacy or New

Market, Legislation

Analytical Consumer

Supplier Community

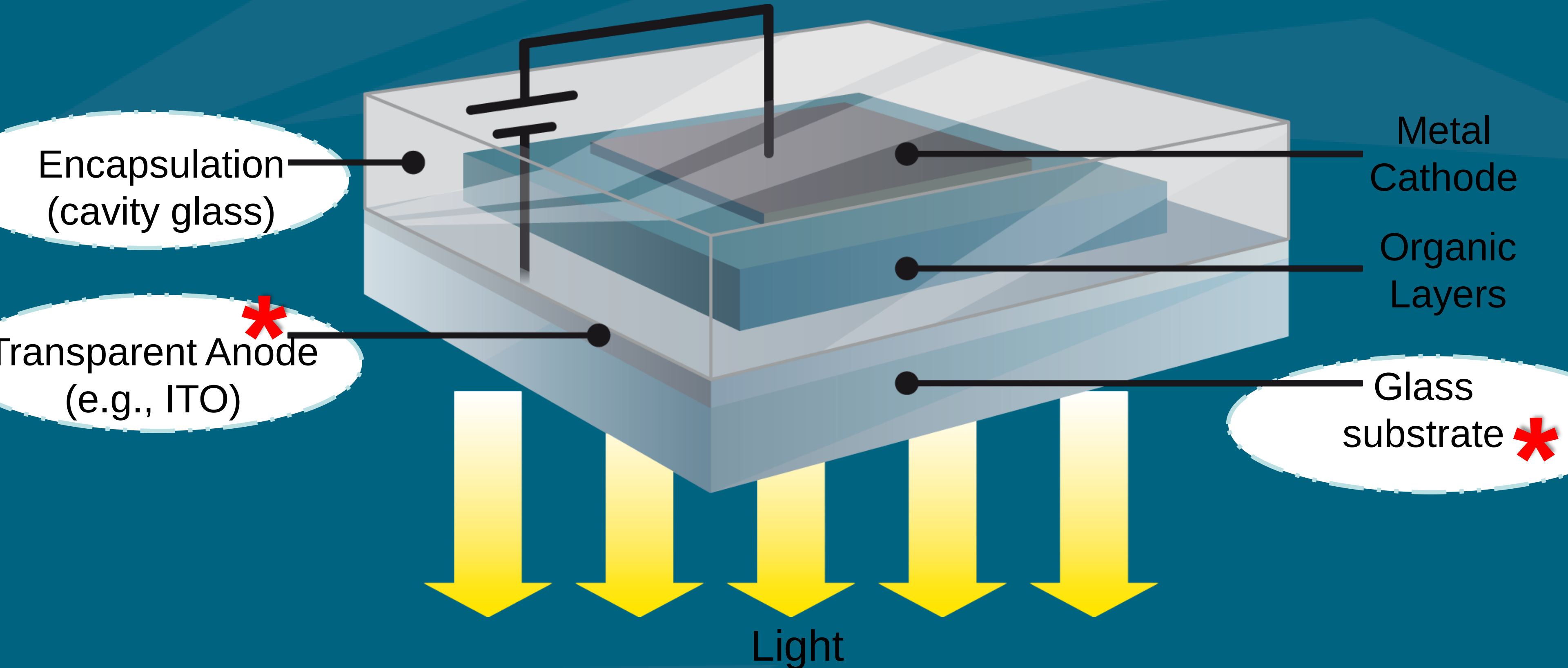


Glass

Mass Market

Price
Performance
Durability
Style
Environment

OLED structure



Glass will be the substrate of choice

Chemically and physically stable, Excellent permeation barrier

Barriers to Broad Market Penetration
Low Lumen/watt, Lifetime, High Fabrication Costs

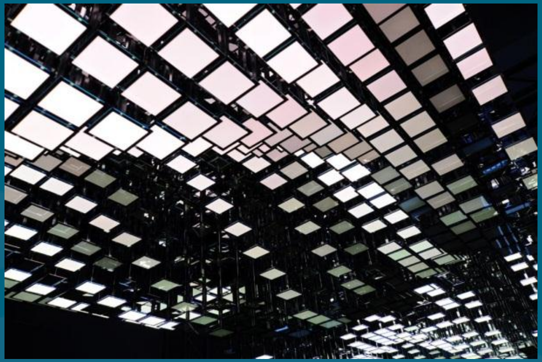
External Quantum Efficiency: EQE = IQE * LEE

Internal Quantum Efficiency

Light Extraction Efficiency

Loss Mechanisms

- Ohmic
- Incomplete injected $e^{-}.h^{+}$ recombination (1 - *IQE*)
- Extraction losses (1 - *LEE*)



Low Cost Integrated Glass For OLED Lighting

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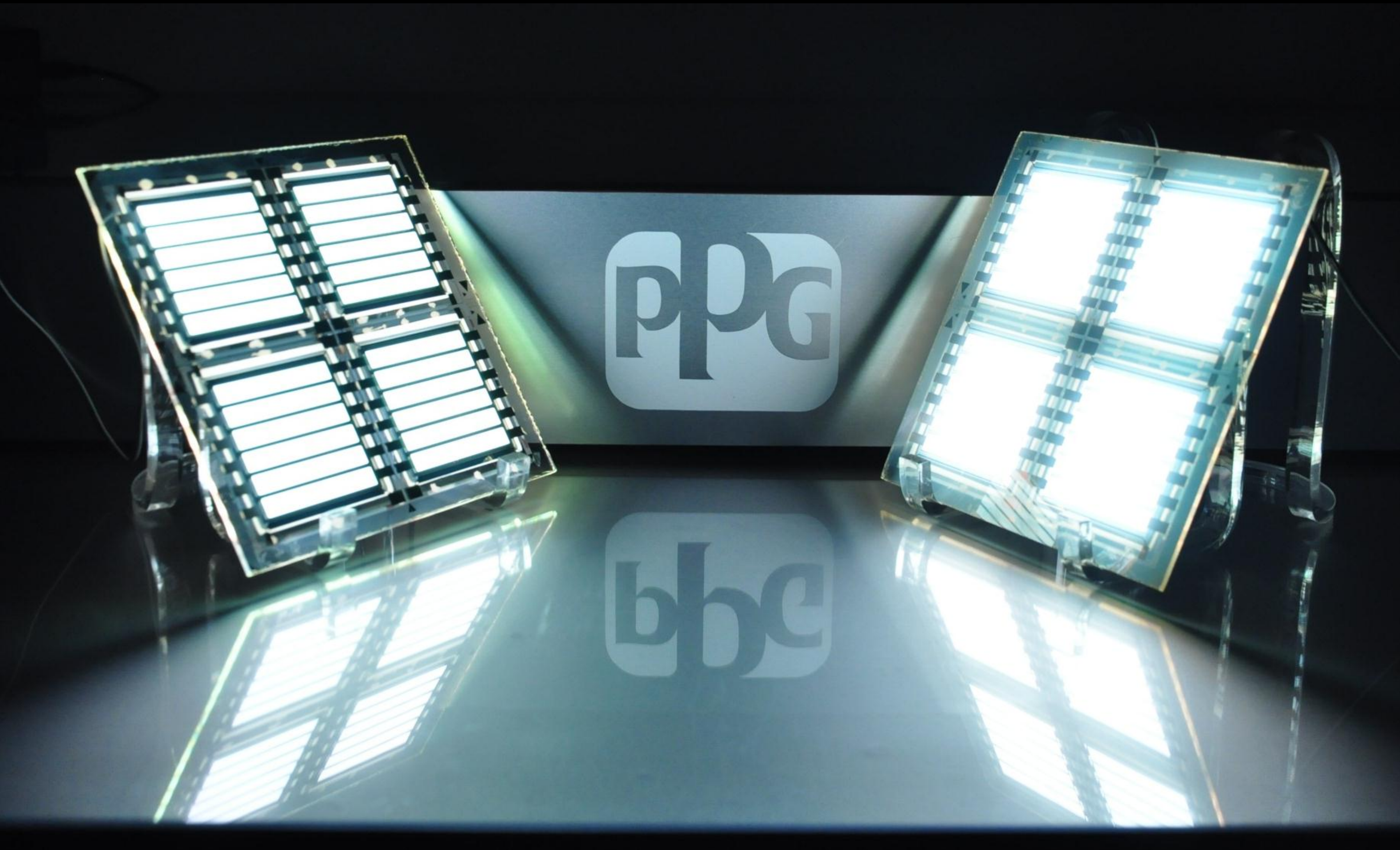

Low Cost Integrated Glass For OLED Lighting
The PPG Roadmap

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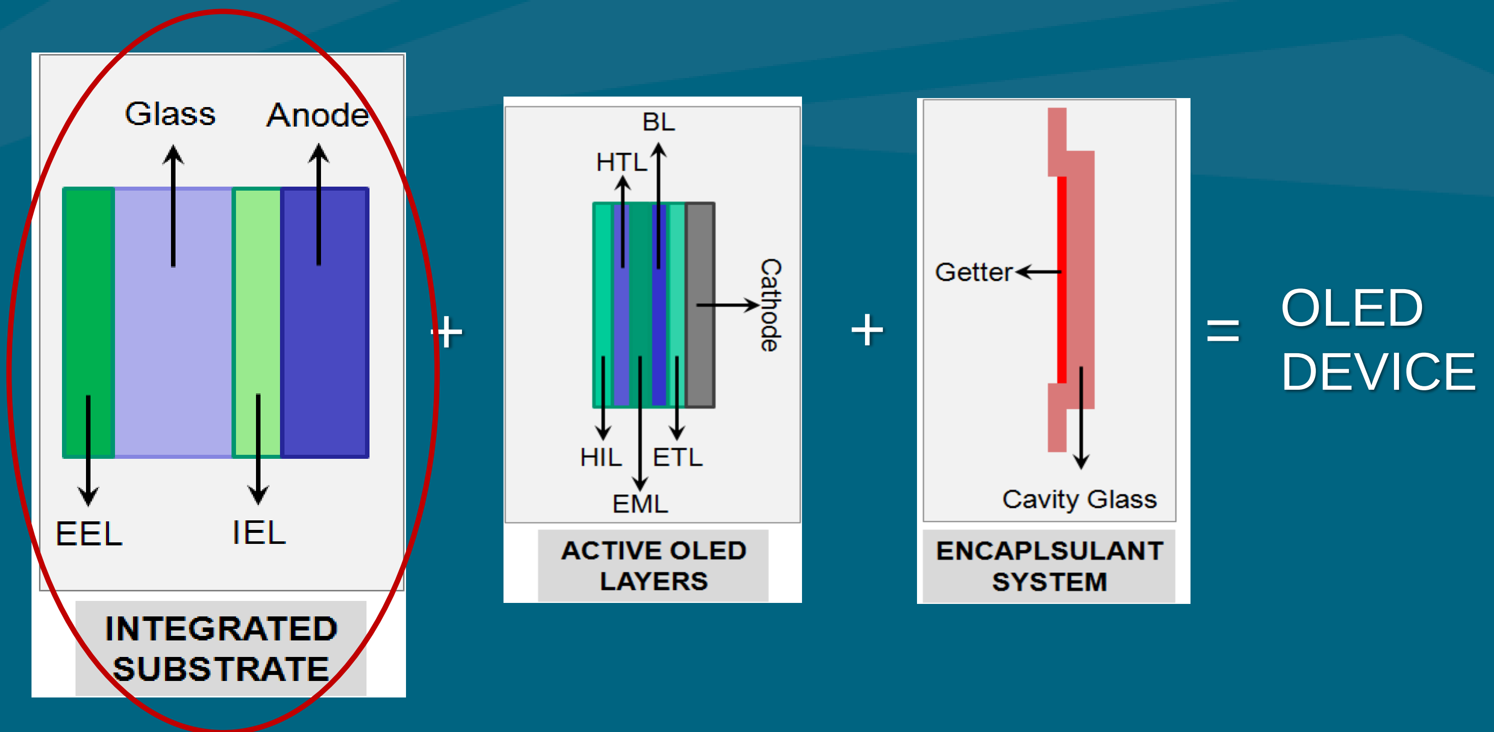

- Integrated substrate for the OLED lighting \$26/m^2 by 2015
- Performance targets per US- DoE's SSL MYPP

(SSLMYPP: Solid State Lighting Multi Year Program Plan)

Project Goal – Meet MYPP Cost Targets

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Rigid Sheet SSL Cost Targets

Stage/Year	Units	2011	2012-13	2014
Depreciation	$/m²	520	200	40
Labor	$/m²	305	45	5
Other Operations	$/m²	70	20	4
Organic Materials	$/m²	30	15	10
Substrate	$/m²	6	6	6
Electrodes	$/m²	20	15	10
Light Extraction	$/m²	20	15	10
Encapsulation	$/m²	10	8	5
Other Materials	$/m²	20	15	10
Total Direct Costs	$/m²	1000	340	100
Total Direct Costs	$/klm	330	57	10

Integrated Substrate Cost Targets

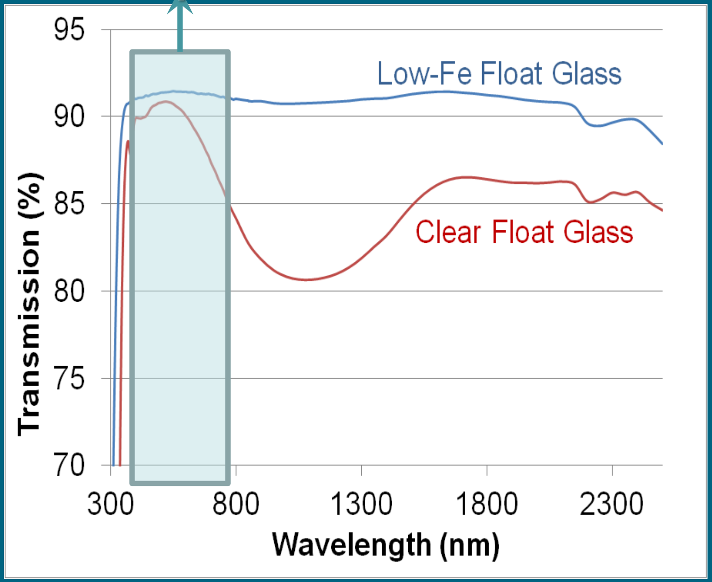
(2010)

2011	2012/3	2014/5
$46	$36	$26

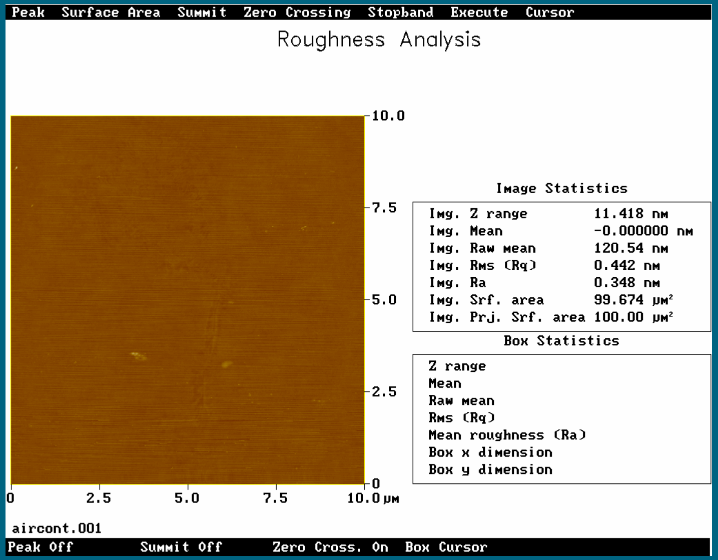
Integrated Glass Substrate

Is Float glass a usable alternative to expensive display glass?

Visible Spectrum



Air Side of glass

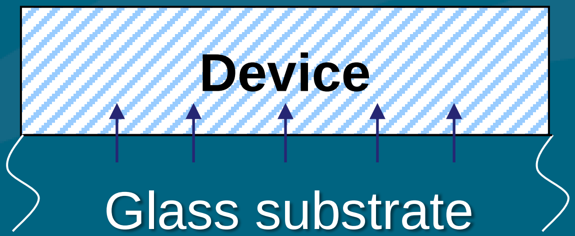


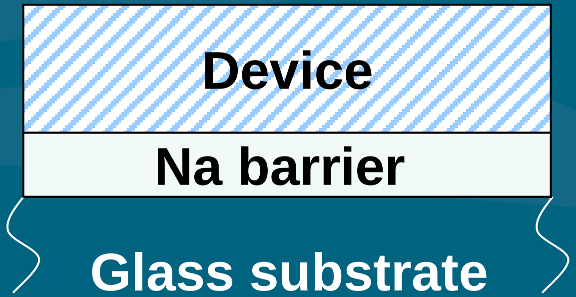
High internal transmission

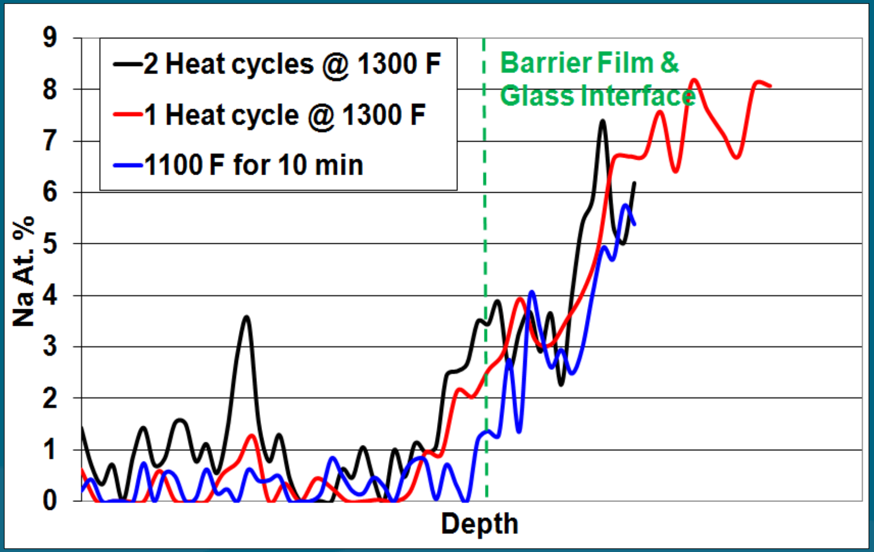
Low surface roughness (<5Å)

Integrated Glass Substrate

Is sodium an issue?

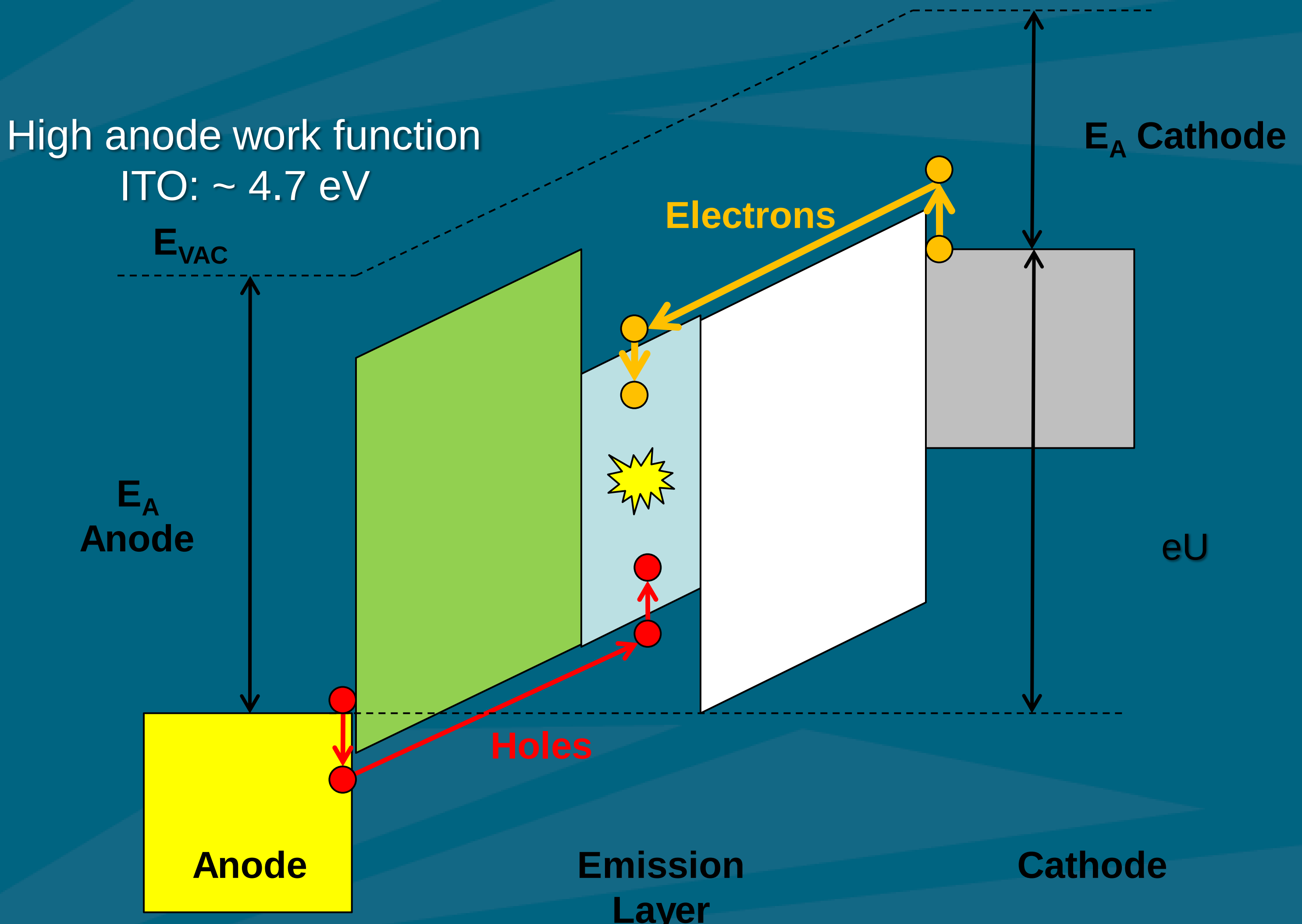




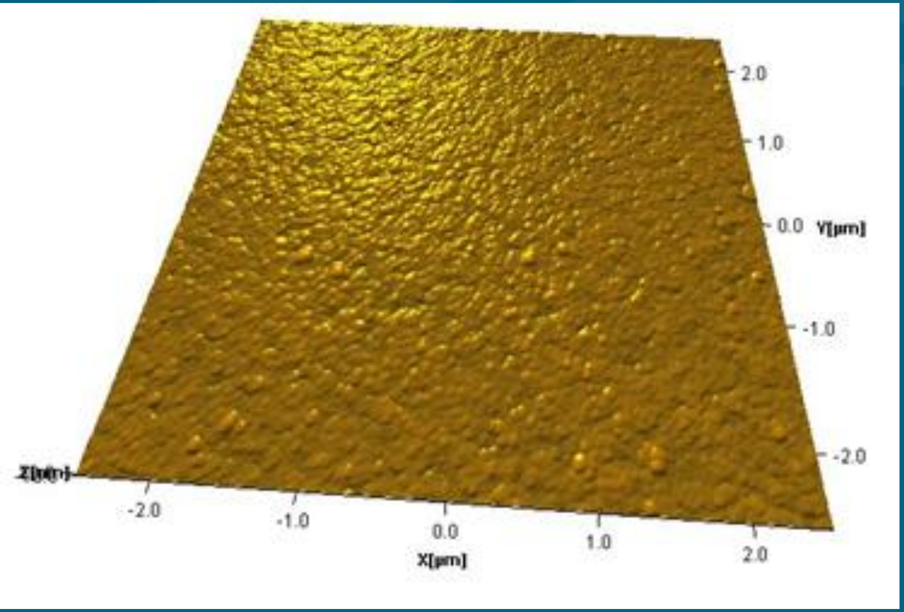


Device Lifetime testing results indicated no need for barrier

Principle function of an OLED



TCO requirements: surface quality

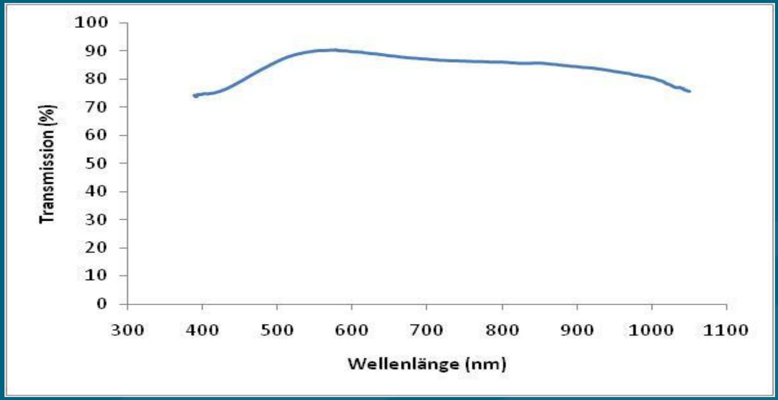


- No spikes (potential shorts; thickness of OLED stacks: few hundreds of nm)
- No particles
- Roughness: difficult to quantify; long-scale waviness uncritical
- Display Quality works (Ra < 1.5 nm, Rmax < 20 nm)

TCO requirements

Conductivity

- Typical spec: sheet resistance < 10 Ohm/sq
- Often metal shunts are used for a homogeneous current injection
- For large area OLEDs, an additional metal grid can be used in the active area

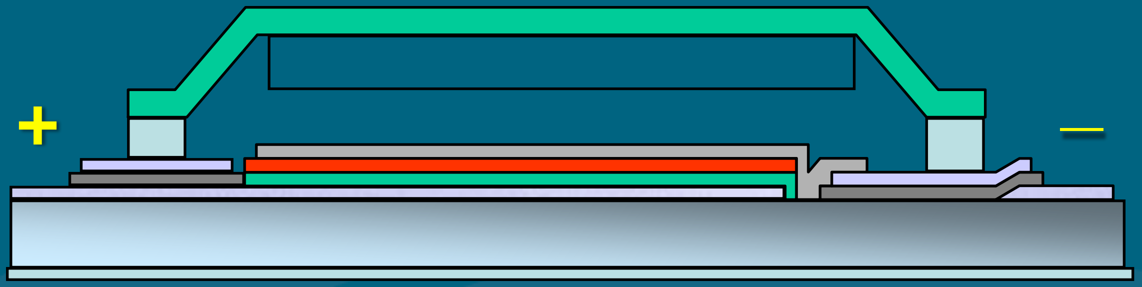


Transparency

- Needed for maximum efficacy: minimum absorption in glass, TCO, organics
- Typical spec for ITO: T_{max} > 85 % @ 550 nm

TCO requirements

- **No formation of hillocks/spikes during operation; no electro-migration**
- **Patternablity (e. g. photolithography, etching)**
- **Resistance to atmospheric & application conditions**
  - ***Contact outside of encapsulation is made on the TCO and/or the metal shunts***



Transparent Anodes

Multiple paths forward

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TCOs (CVD, PVD)

- FTO: Standard Flat Glass Process Exists
- ITO: Industry-standard, expensive, high temperature
- IZO: Evolving material
- AZO: Durability, High Temperature

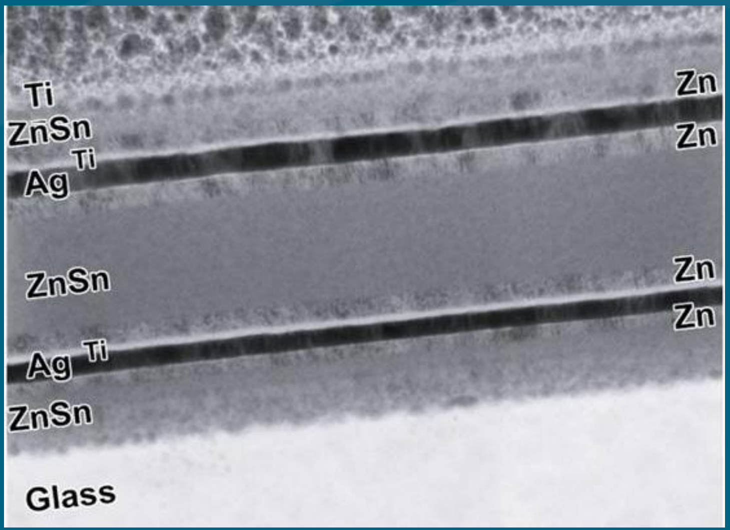
Metallic (PVD)

- Room Temperature Process
- High conductivity
- 3 or more layer stacks
- Flat Glass Manufacturing Competency

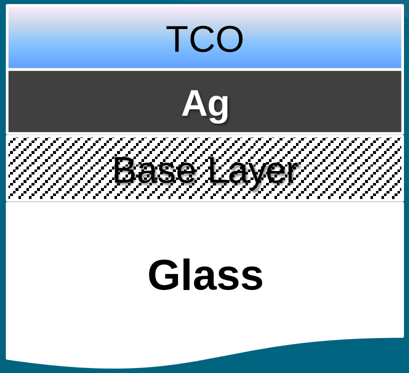
Optical & electronic stack design & Morphology will be critical

Transparent Metallic Conductors on Glass

Solar Control & Low-Emissivity Coatings



Simple 3-layer Anode



- Highly developed design and manufacturing capabilities
- OLED process & service stability must be established

Integrated Glass Substrate

The Anode Status

- Room temperature & high temperature PVD and on-line CVD processes

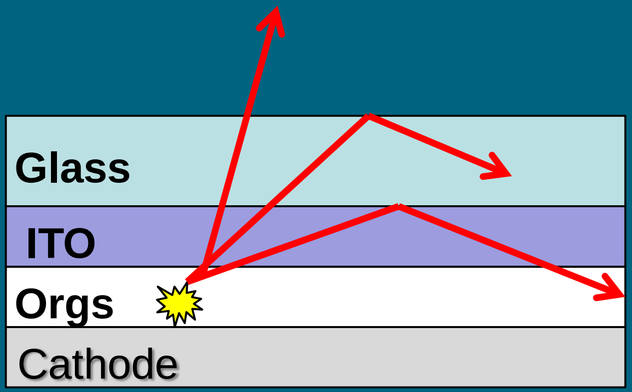
Coating Type	Sheet Resistance (Ω/□)	Transmission @ 550nm	RMS Roughness (nm)	Work Function
Control	18	83	3	5.2
Anode 1	10	85	14	4.96
Anode 2	8.5	84	6	5.08
Anode 3	21	84	1	5.4
Anode 4	7.3	89	0.5	5.33
Targets	***10***	***85***	***2***	***>5***

Target Properties met with multiple anode designs

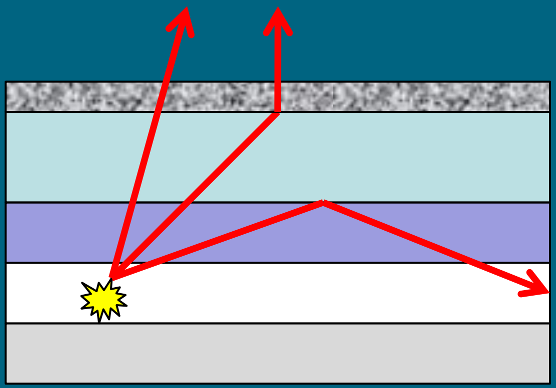
Substrate Requirements
External Light out-coupling

Fraction of photons leaving OLED: ~ 20%
(Interfacial and total internal reflections)

With External Light out-coupling
⇨ ~ 28%



Standard



Commercially available micro lens array or scattering foils

Integrated Glass Substrate

External Extraction

1.27x light enhancement on 2.0mm substrates, white PHOLED device

Parity with standard diffuser sheet, No significant shift in color

Sample Type	CIE x	CIE y	Output (Lumens)	Enhancement
Control (No EEL)	0.412	0.409	5.77	1.00x
EEL	0.412	0.404	7.3	1.27x
Control + Diffuser	0.423	0.406	7.54	1.31x

The Solution is Scalable

Substrate requirements

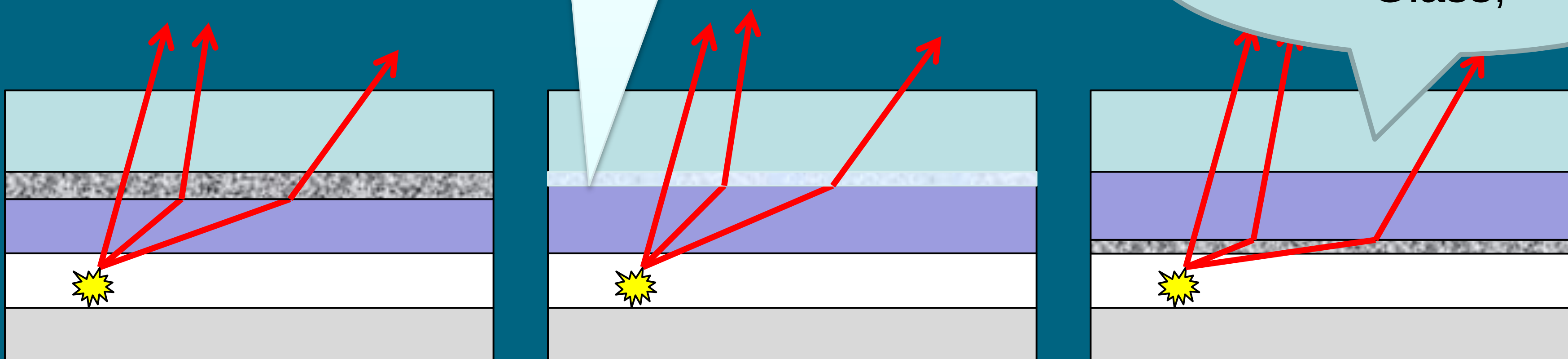
Internal light out-coupling

Lithographic Designs

High-n scattering la
between glass and anode

ace with
moothening layer

Higher Index Glass,

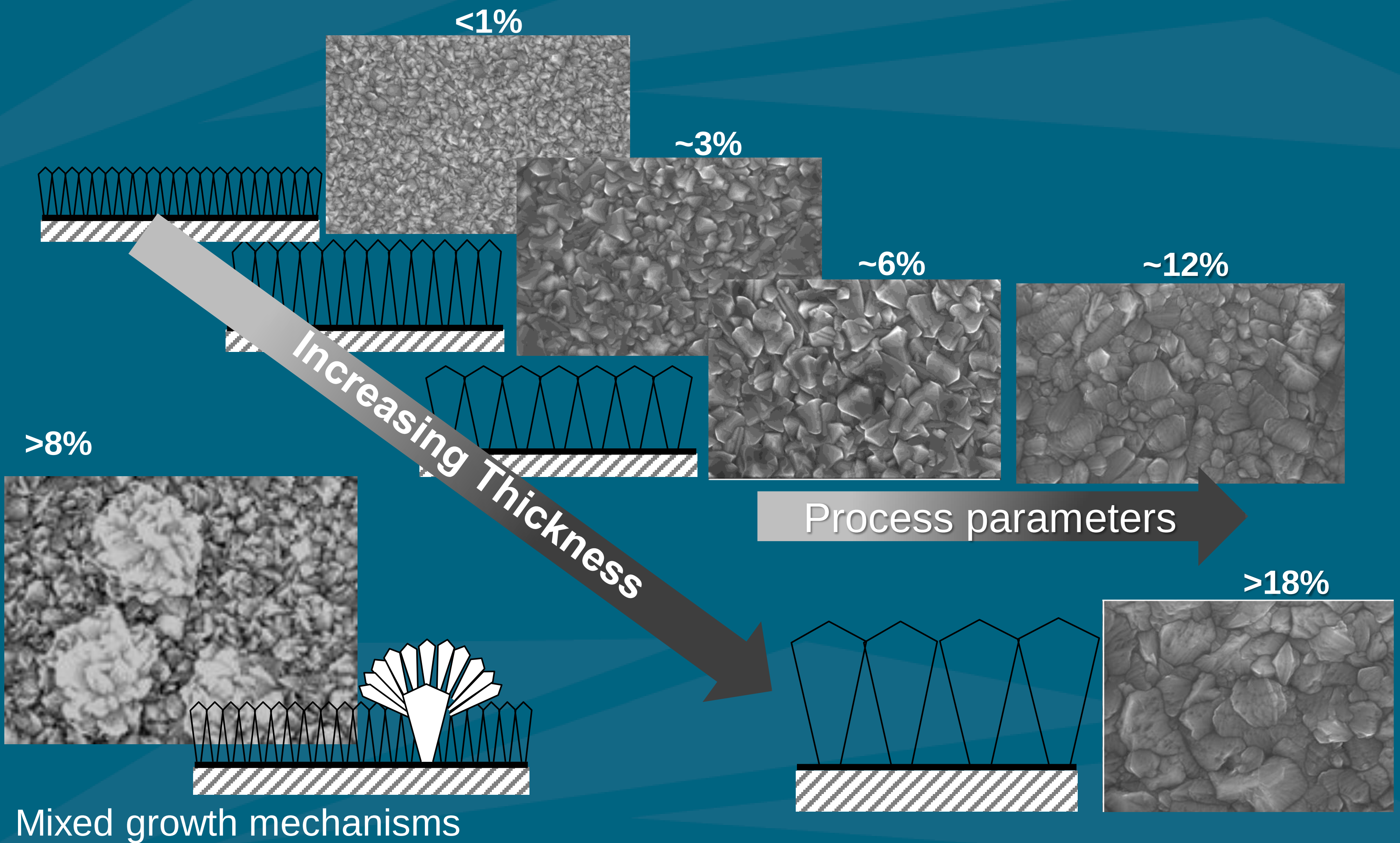


Is TCO surface still compatible with OLEDs?

Many papers and patents, but no substrates commercially available!

Lessons from TCO Glass for Solar

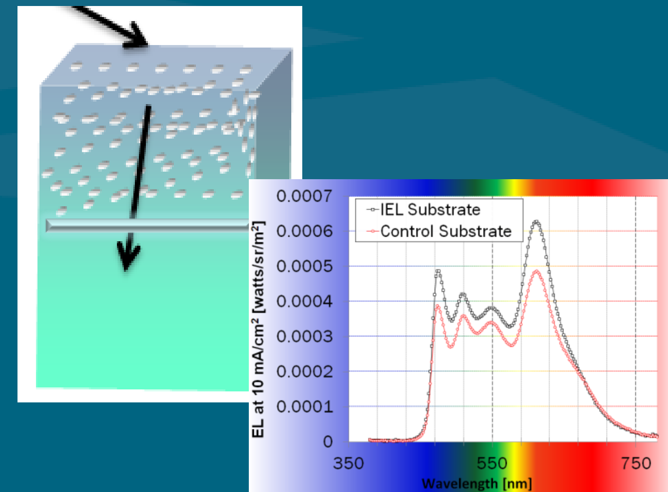
Light Scattering at the TCO Interface

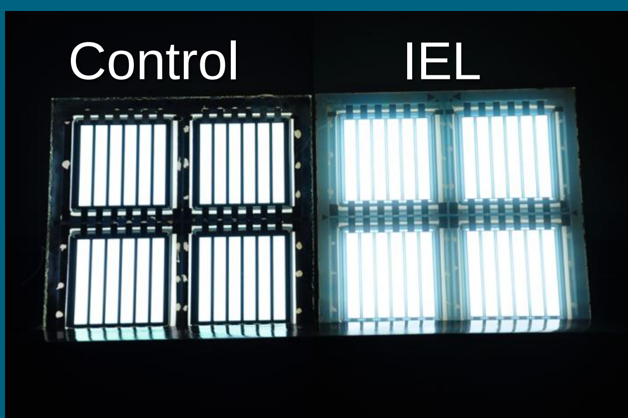


Integrated Glass Substrate

Internal Extraction

- **1.31x** enhancement (to be optimized)
- **1.73x** in combination with acrylic block EEL
- Low-cost, scalable, anode-compatible
- Still too rough





6” white OLED panels

	At J=2mA/cm^2							
Substrate	**Voltage (V)**	**PE (lm/W)**	**1931 x**	**1931 y**	**CCT [K]**	**Δuv**	**Extraction Factor**	**Extraction Factor with 12mm acrylic block**
Control	4.12	36.8	0.41	0.436	3722	0.02	NA	1.45x
IEL	3.98	48.3	0.399	0.43	3920	0.02	1.31x	1.73x

Device data for white PHOLED device on IEL substrate

Sample Type	Transmission (%)	Haze (%)	Enhancement
Sample I	69.3	33.2	1.26x
Sample II	73.3	29.5	1.31x

Variation of Enhancement factor with optical properties

Integrated Glass Substrates for Solid State OLED Lighting

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Conclusion

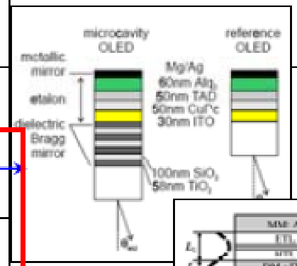
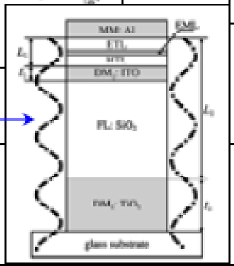
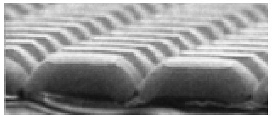
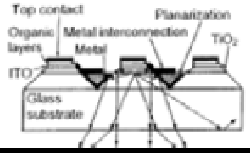
- OLED lighting technology is highly promising
  - Cost, and light extraction remain major challenges
  - Glass technology will be key to successful commercialization
- We have demonstrated a combination of low-cost integrated glass substrate technologies
- The development must be in collaboration with the lighting industry

Acknowledgement

- Abhinav Bhandari, PPG
- Dennis O’Shaughnessy, PPG
- Manfred Ruske, Phillips
- Universal Display Corporation
- US Department of Energy

Additional Slides

Light Extraction Technology comparison: Lit. Review

Schemes	Features	Factor (conventional=1.0)	Ref.
Conventional Dielectric Mirror		1.5 ~ 5 (for individual colors)	Tokito *et al.*, J.Appl.Phys. 86, 2407 (1999)
Multi-wavelength Resonance Cavity		1.3	Shiga *et al.*, J.Appl.Phys. 93. 19 (2003)
Top Emission		1.0 ~1.2	Kanno *et al.* Appl. Phys. Lett. 86, 263502 (2005)
Microlens		~1.5	Möller et al. J.Appl.Phys. 91, 3324 (2002)
Patterned/shaped Substrates		~1.9	Garbuzov et al. Opt. Lett. 22, 396 (1997)

- *Source: Report from Korea Institute of Technology authored by Byung Doo Chin*

A detailed Comparison……….

	Incandescent	Fluorescent	LEDs	OLEDs
Efficacy	17 lm/W	100 lm/W	80-120 lm/W: White 65-80 lm/W: warm white	**100 lm/W : CRI 70** **71 lm/W : CRI 81**
CRI	100	80-85	80 – white 90 – warm white	**95 with 40 lm/W**
Form Factor	Heat generating	Long or compact gas filled glass tube	Point source high intensity lamp	**Large area thin diffuse source. Flexible, transparent**
Safety concerns	Very hot	Contains mercury	Very hot in operation	**None to date**
LT70 (K hours)	1	20	50	**> 20 with 68 lm/W** **> 4 with 100 lm/W**
Dimmable	Yes, but much lower efficacy	Yes, efficiency decreases	Yes, efficiency increases	**Yes, efficiency increases**
Noise	No	Yes	No	**No**
Switching lifetime	Poor	Poor	Excellent	**Excellent**
Color Tunable	No	No	Yes	**Yes**

Displayed products: Revel & kindred from winona lighting

- Efficacy: 51 Lumens/Watt
- Light Output: 370 Lumens
- CCT: 3500K
- CRI > 80
- Power Consumption: 7.3 Watts
- Lamp Life (LT 70): 15,000 hrs

REVEL

KINDRED

- Efficacy: 51 Lumens/Watt
- Light Output: 3382 Lumens
- CCT: 3500K
- CRI > 80
- Power Consumption: 66 Watts
- Lamp Life (LT 70): 15,000 hrs

These OLED panels use Phosphors produced by PPG's Optical Products

Building Energy Demand Challenge:

End-Use Energy Consumption

- Buildings consume 39% of total U.S. energy
  - 71% of electricity and 54% of natural gas