OLED Light Extraction Status and Needs

Michael Boroson,
Co-Founder and CTO OLEDWorks

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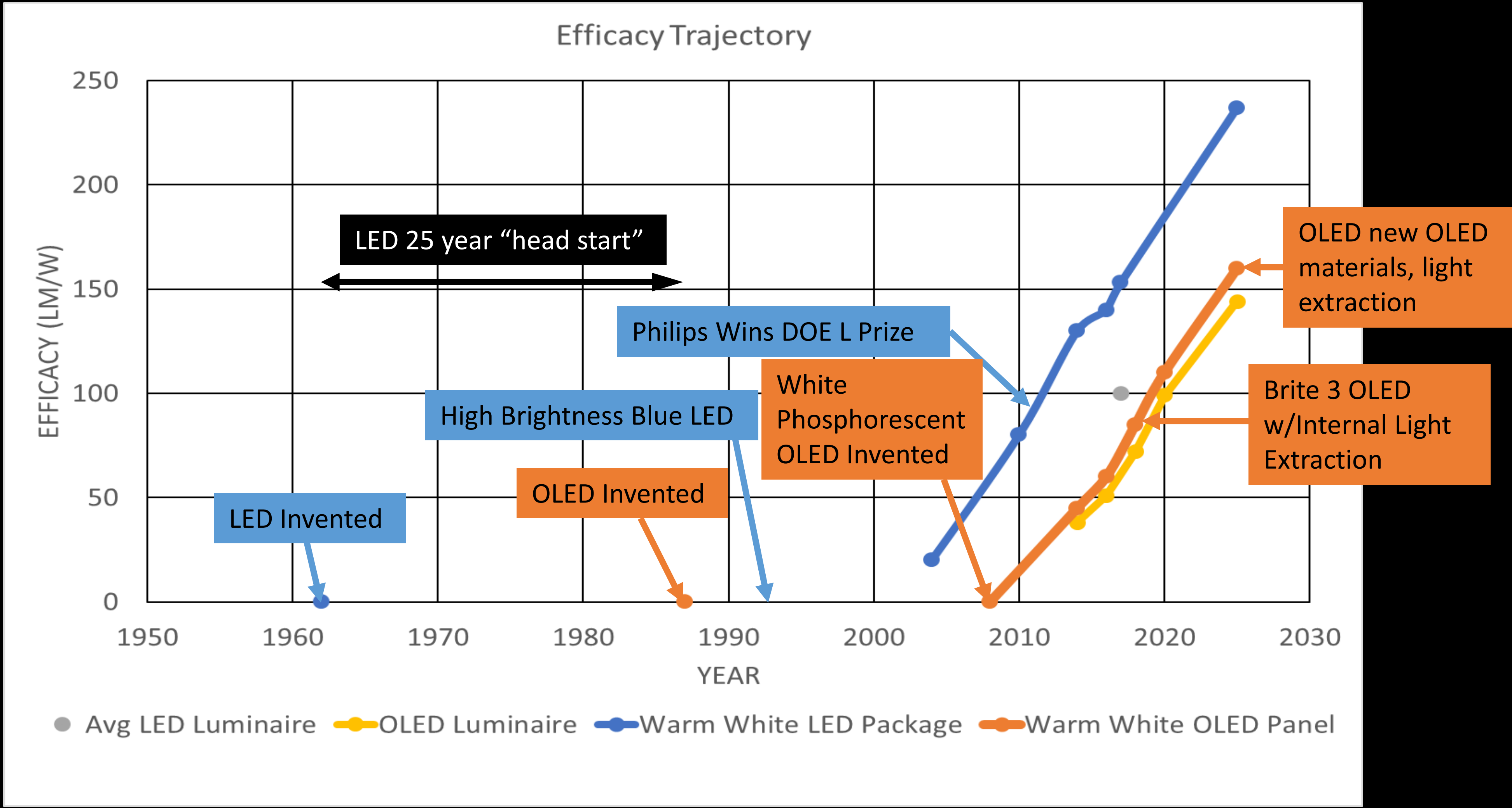
January 29, 2020

OLED vs. LED Efficacy Trajectories

Currently only extract ~50-55% of photons to air

DOE target is 70%

Efficacy would be ~110-120 lm/W at 70% with hybrid OLED



OLEDWorks Naturally Illuminating

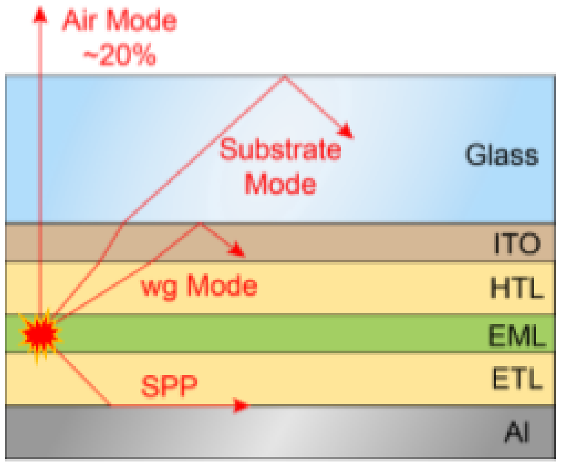
Where are the Photons?

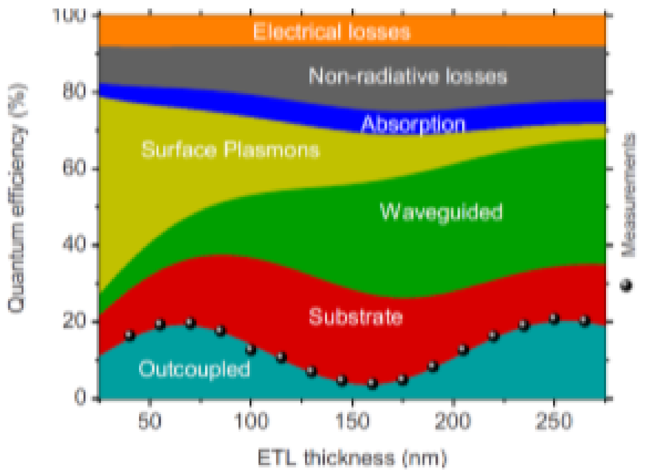
100% Phosphorescent
Vs.
Hybrid Fluorescent Blue + Phosphorescent G/R

Single Stack OLED
- High loss due to surface plasmons
Vs.
Multi-Stack OLED
- High loss due to waveguided photons

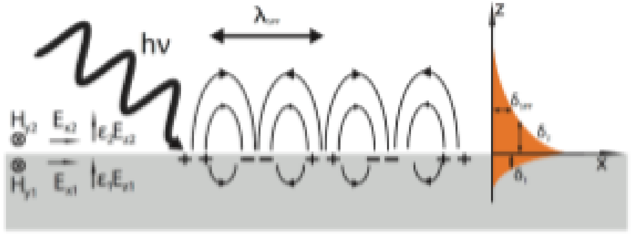
80% of Light is Trapped in the OLED

- $\eta_{EQE} = \eta_{IQE}\,(\sim 100\%) \times \eta_{Ext} \approx$ 20%





- OLED Loss Channels
  - Substrate mode
  - Waveguide mode
  - **Surface plasmon polariton (SPP)**
  - **Metal absorption**



Forrest, S., "No Photon Left Behind: Challenges in OLED Outcoupling", DOE SSL Workshop, 2019.

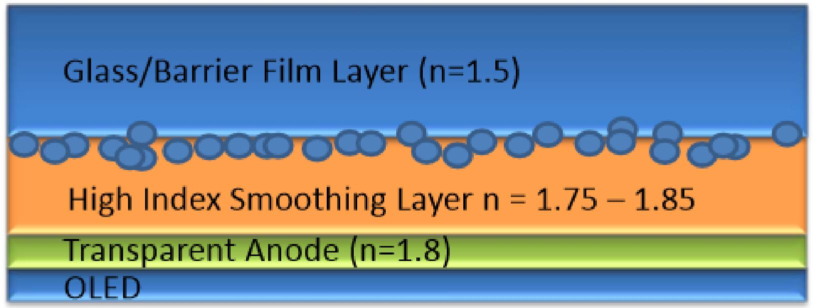
Light Extraction Requirements

- Low cost and scalable
- Thin
- Extract all substrate and waveguide mode photons (all wavelengths)
- Low absorption
- Compatible with rigid and bendable substrates
- No color change with viewing angle
- No detrimental impact on initial yield (e.g. low roughness, no defects)
- No detrimental impact on luminance lifetime (e.g. no contaminants)
- No detrimental impact on reliability (e.g. shorting, thermal resistance, thermal shock, vibration, humidity resistance, etc.)
- Compatible with current manufacturing lines and future R2R lines

Current and Advanced Scattering Light Extraction

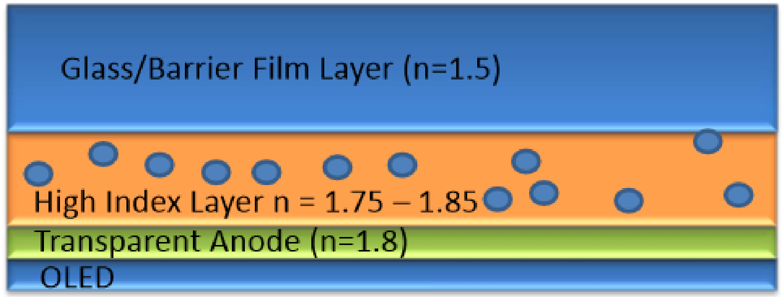
Generation 1

- Condensed Scattering Layer with high index smoothing



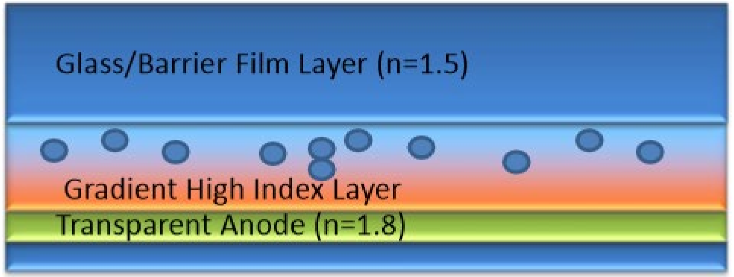
Generation 2

- Distributed Scattering Layer with high index layer



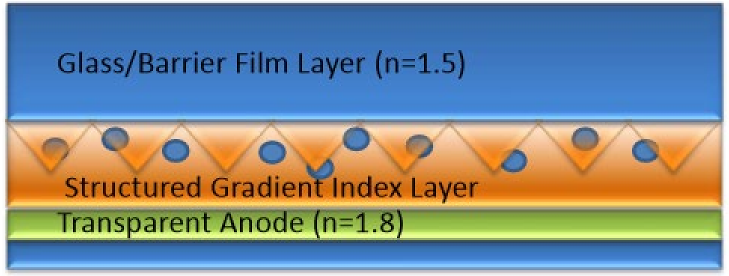
Generation 3

- Distributed Scattering Layer with gradient high index layer



Generation 4

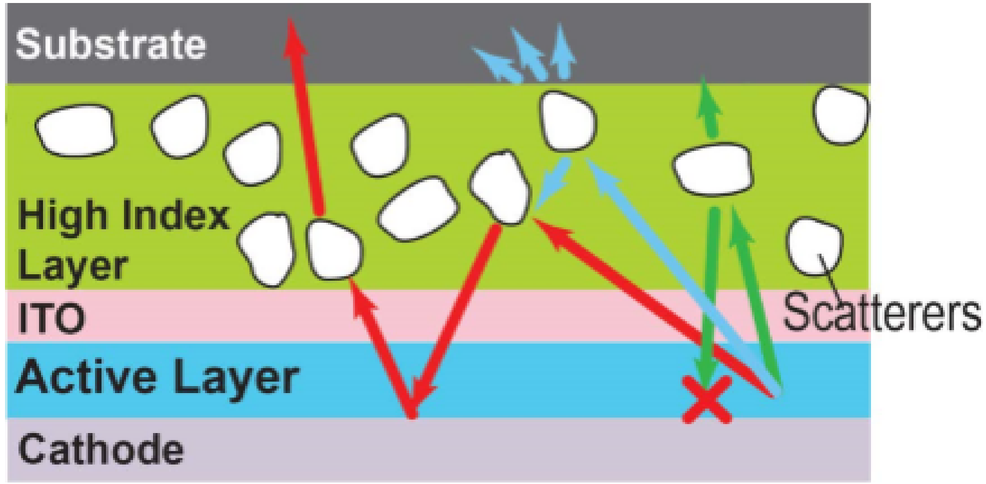
- 3-dimensional graded index with or without scatterers



Cooper, G. et al., "Overview of Pixelligent's OLED Lighting Program", OLEDs World Summit, 2015.

Scattering Light Extraction Issues

- Scattering is a random process
  - Limited ability to control which light gets scattered and direction of scattering
- Improved light extraction relies on multiple passes through the device
  - Maximize reflection at cathode
  - Minimize absorption
  - Minimize path length through device – enough scattering



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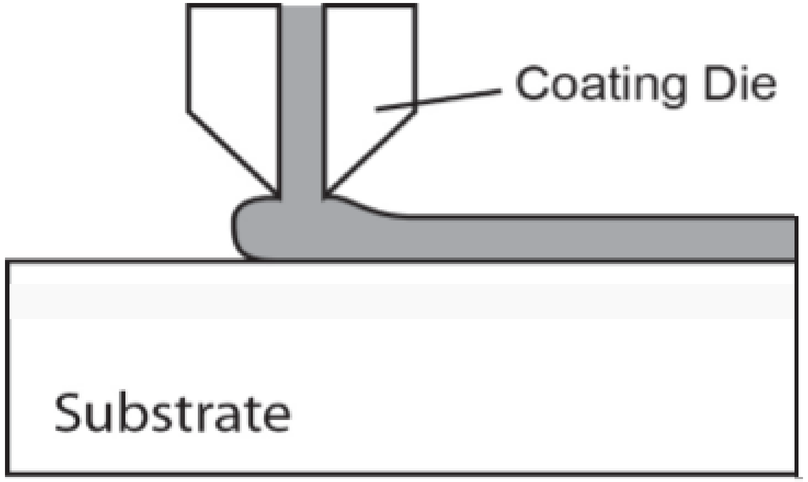
Manufacturing of Scattering Type Light Extraction



- Pixelligent Formulation compatible with multiple deposition methods – *slot-die*, spin coat, inkjet, spray coat, …
- Not dependent on substrate – flexible or rigid, film or glass,
- Pattern with slot-die, inkjet, uv patterning, …

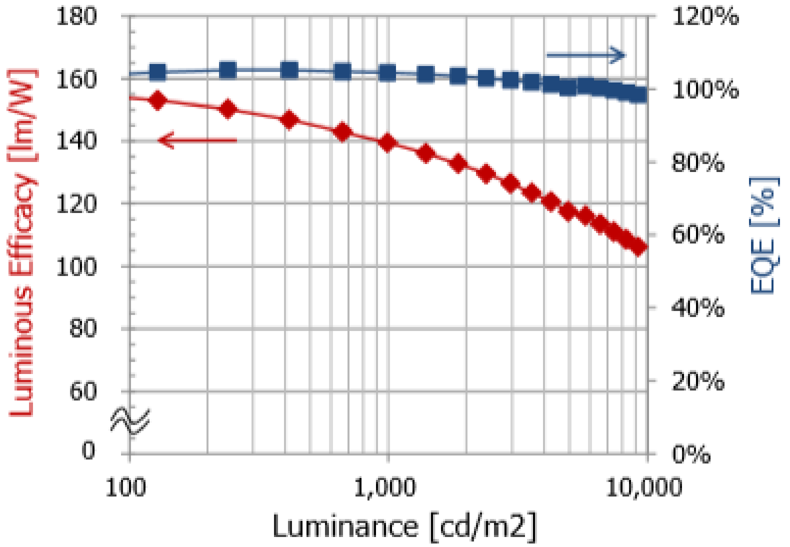
Cooper, G. et al., "Overview of Pixelligent's OLED Lighting Program", OLEDs World Summit, 2015.

Scattering Light Extraction + 100% Phosphorescent

Recent progress : W-OLED with 139lm/W

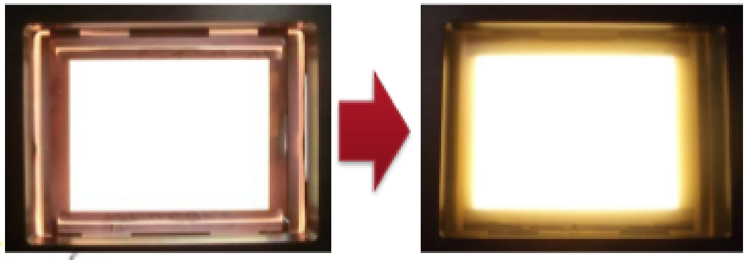
KONICA MINOLTA

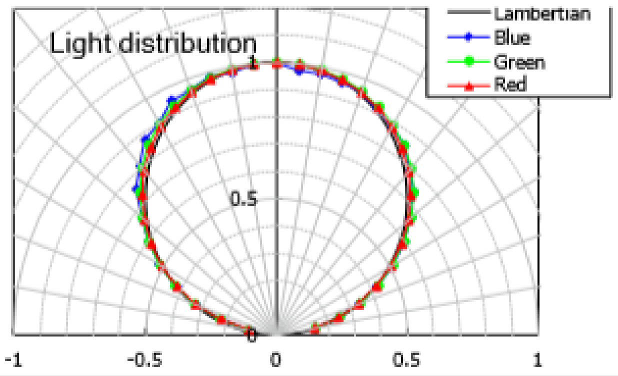
Panel on Glass with IES		
Efficacy	lm/W	139
Luminance	cd/m^2	1,000
EQE	%	104.5
Voltage	V	5.3
CCT	K	2,857
1931 CIE	(x,y)	(0.47,0.44)
CRI	Ra	81
Estimated LT50	hrs	> 55,000
Emissive area	cm^2	15



w/o IES : 61 lm/W

w/ IES : 139 lm/W





Symfos

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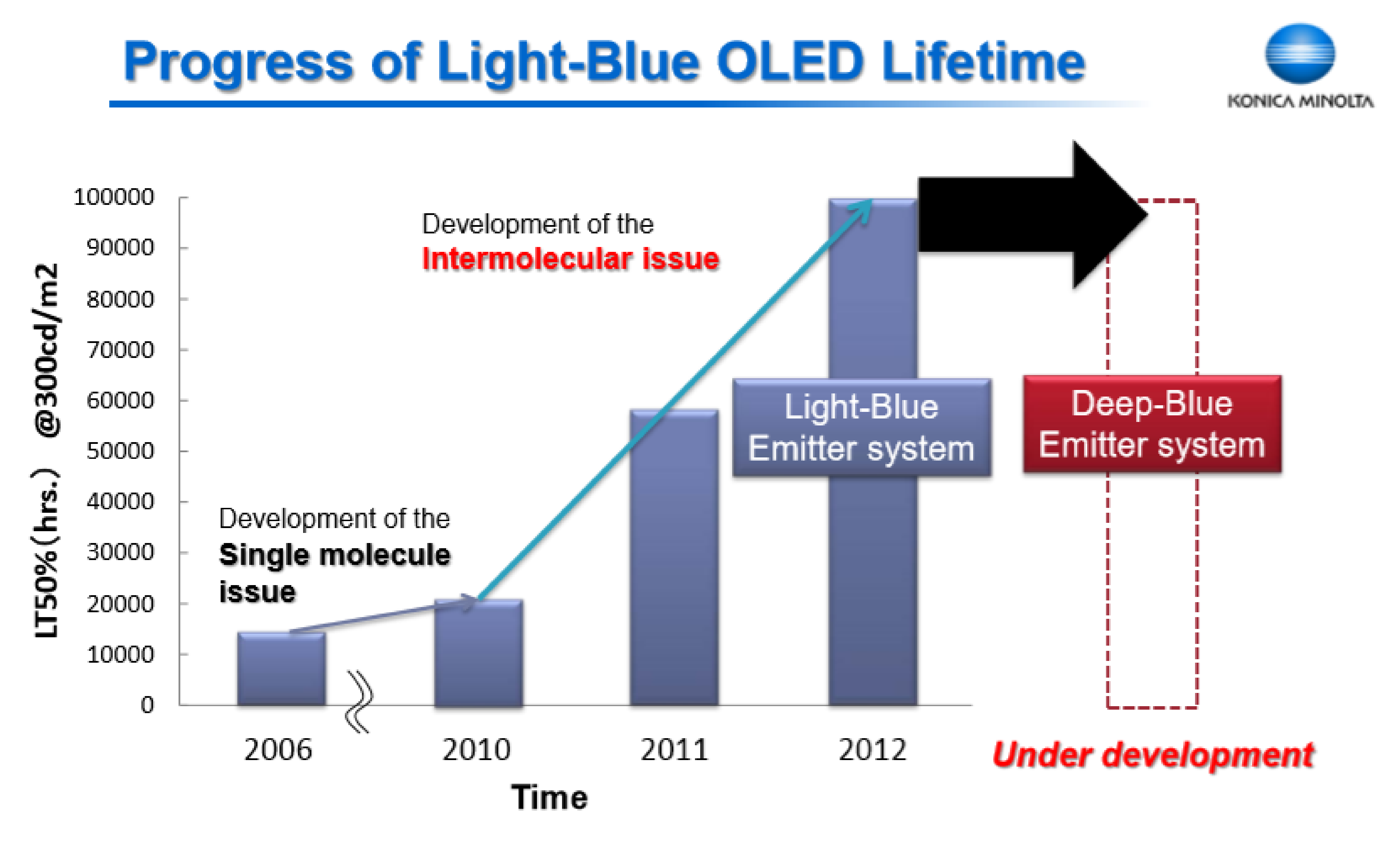
Tsujimura, T., “Thin and Feather-light Weight Flexible OLED Manufactured by Roll to Roll Method”, OLEDs World Summit, 2015.



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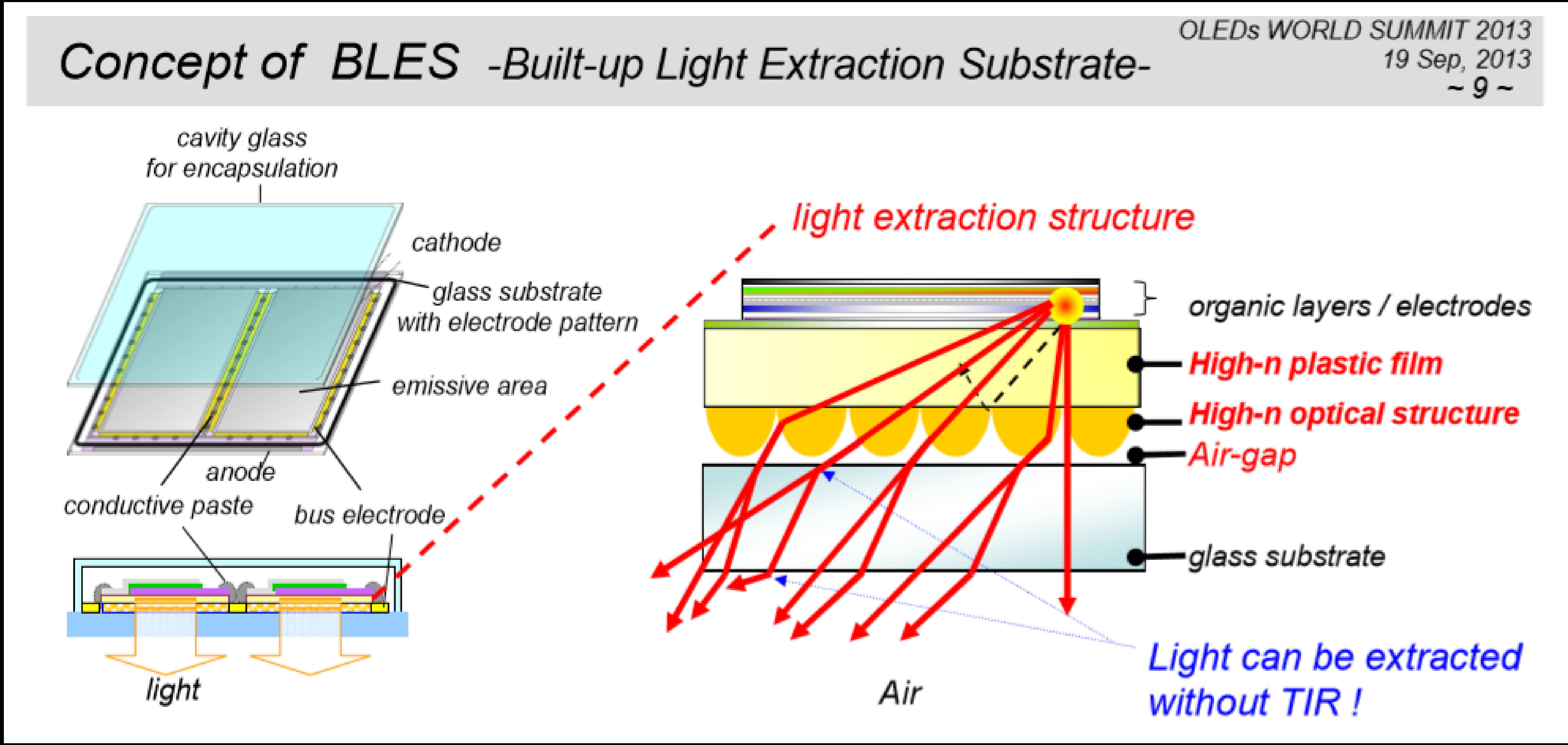
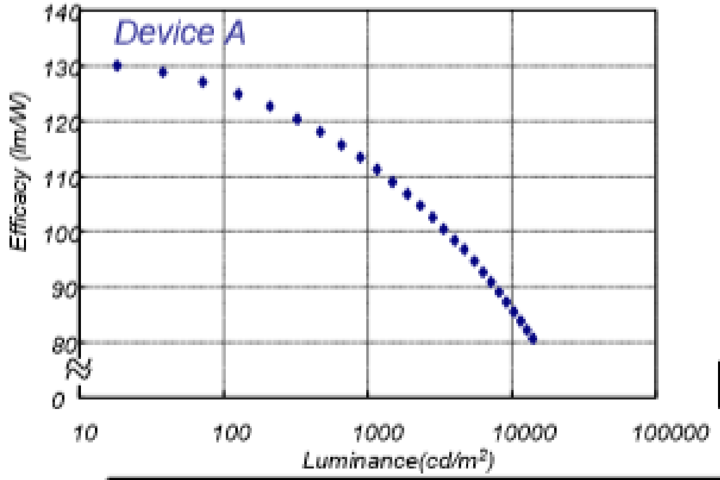
High Index Substrate and Micro-Lens Array

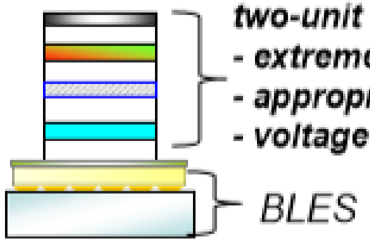


Komoda, T., "Novel Light Extracton Technology and Its application to Highly Efficient White OLEDs", OLEDs World Summit, 2013.

High Index Substrate and Micro-Lens Array



Quite high efficacy of 114 lm/W white device was realized !



	presented at SID2012	Device A (This Study)	
Luminance	1,000 cd/m²	1,000 cd/m²	3,000 cd/m²
Efficacy	101 lm/W	**114 lm/W**	102 lm/W
External quantum efficiency (estimated LEE)	84 % (~ 42 %)	**99 % (~ 50%)**	←
Driving voltage	5.9 V	**5.5 V**	6.0 V
Estimated lifetime (LT_{70})	~10,000 h	~ 40,000 h	~10,000 h
Estimated lifetime (LT_{50})	~30,000 h	~120,000 h	~ 30,000 h
CRI	86	80	←
Color coordinates	(0.44,0.44)	(0.48,0.43)	←
Color temperatures	3,200 K	2,550 K	←
Emissive Area	1 cm²	1 cm²	←

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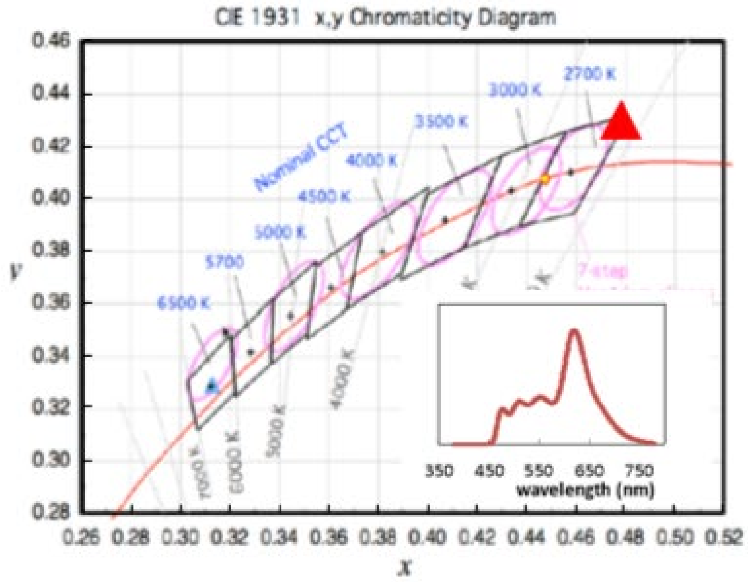
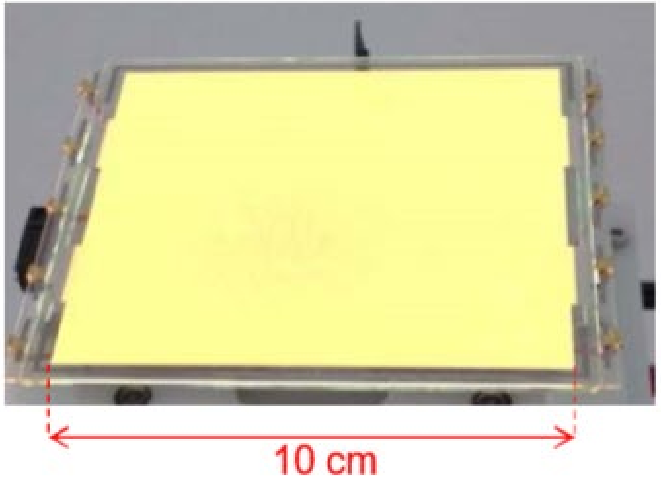
High Index Substrate and Micro-Lens Array

Luminance	1,000 cd/m²
Efficacy	133 lm/W
EQE*	56 %
Estimated LT_{50}	>150,000 h
Estimated LT_{70}	> 40,000 h
Driving Voltage	5.4 V
CRI	84
Color Coordinates CIE 1931	(0.48 , 0.43) meets ENERGY STAR® criteria
CCT	2,600 K
Emissive Area	100 cm²

* EQE per unit. Raw data = 112 % at 2 units

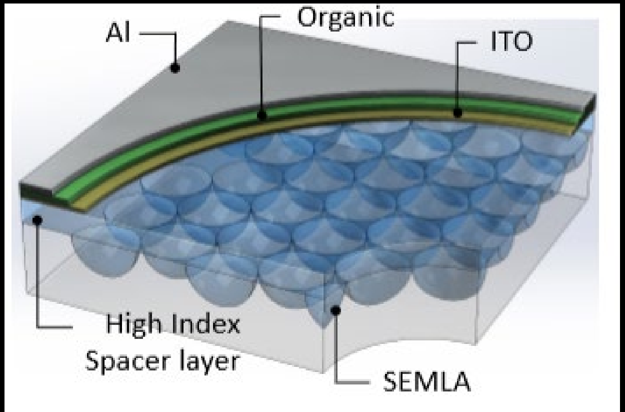


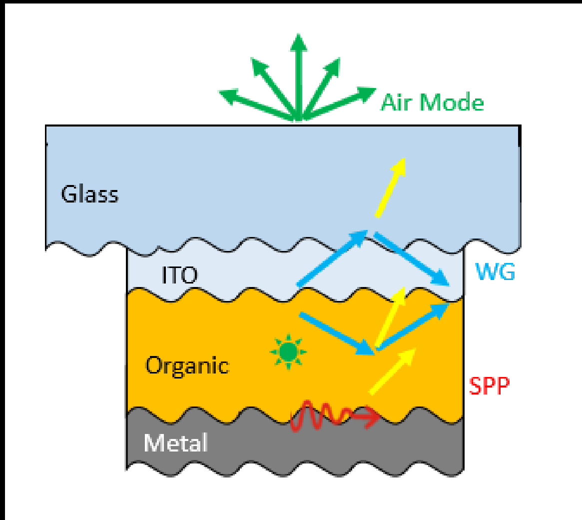


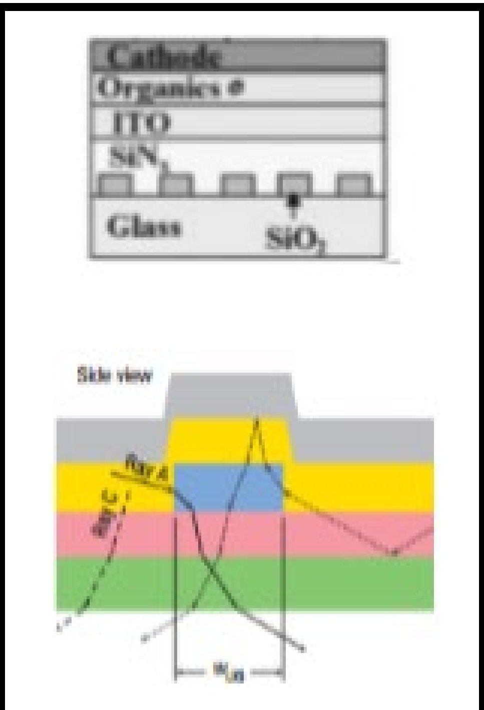
Komoda, T., “Recent Progress of OLED Technologies for Lighting Application”, OLEDs World Summit, 2014.

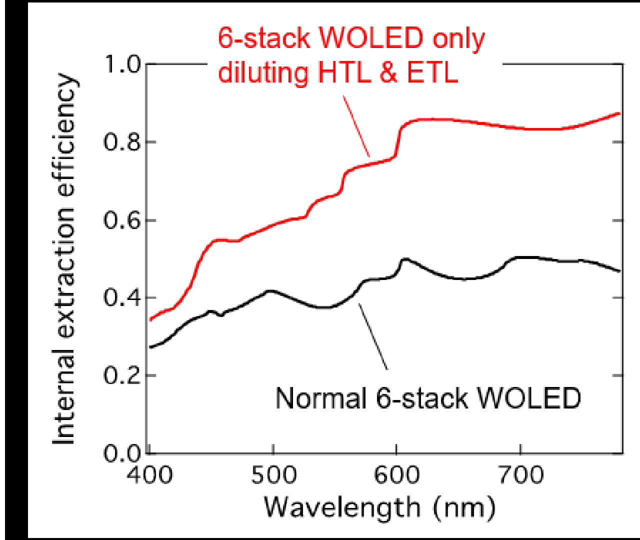
Advanced Light Extraction Technologies

Scattering + 2D or 3D index gradient
Sub-electrode optical gratings or photonic crystals
Corrugations or grids in OLED
Molecular dipole orientation
Decrease of OLED layers refractive indices
Sub-electrode micro-lens arrays
Dielectric diffusers
Ultra-thin roughened substrates









Forrest, S., “No Photon Left Behind: Challenges in OLED Outcoupling”, DOE SSL Workshop, 2019.

So, F., “Effects of Nano-Structure and Refractive Index on Light Extraction in OLEDs”, DOE SSL Workshop, 2019.

Geibink, C., “Improving OLED performance via semiconductor dilution”, DOE SSL Workshop, 2020.

Current Status: Market Segment Readiness

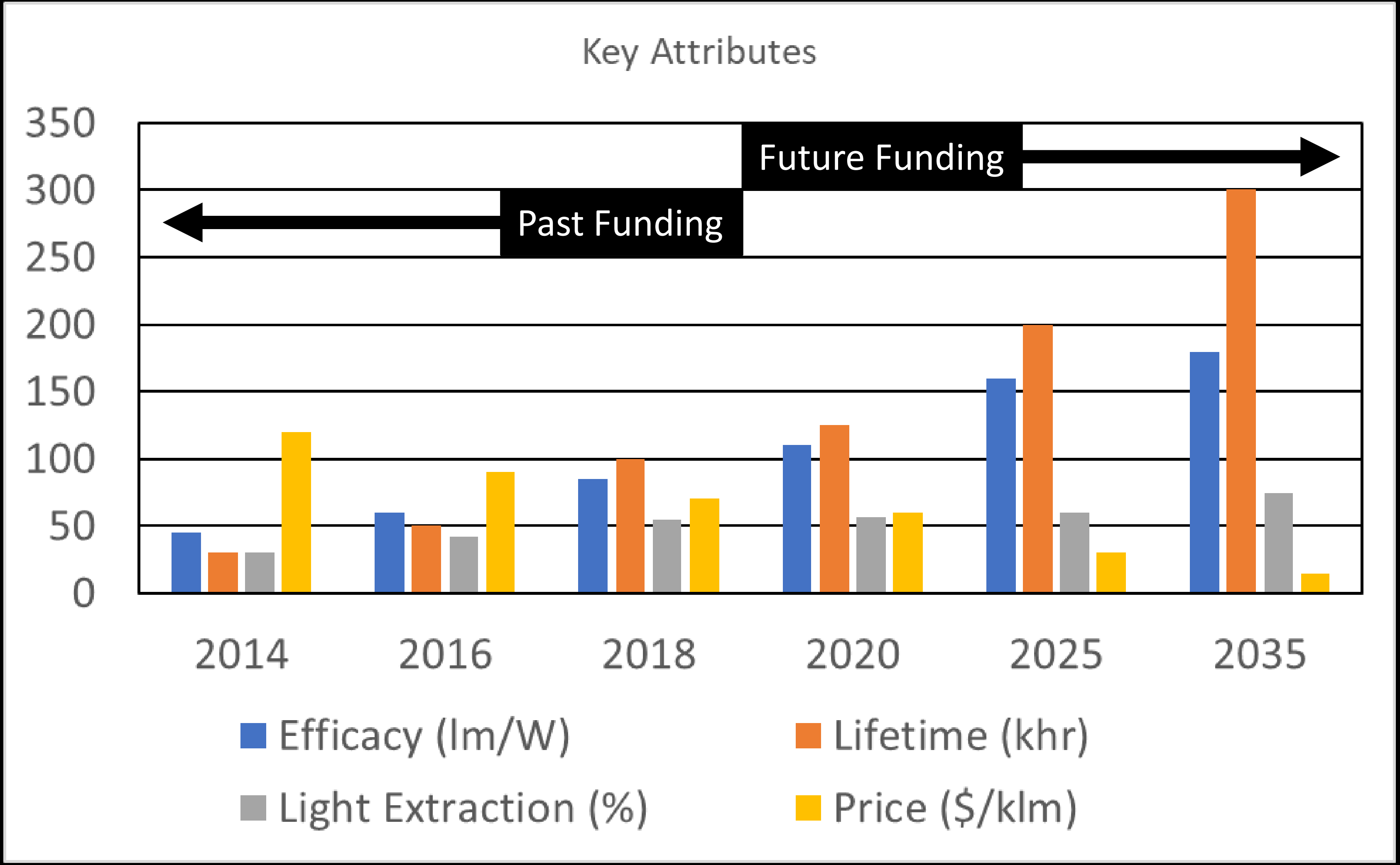
Peter Ngai
VP OLED Lighting
Acuity Brands Lighting
7th China International OLED Summit
1/25/18

All require:
3,000+ cd/m^2
>90 CRI
1.5-2 MacAdam Color Consistency
10-15 year Shelf Life

Lumen Application	High End Early Adopters	Main Stream Early to Late Majority
Low (perception of light) ~100-~400 lumens 1-2 Panels	Efficacy: 40 lm/W Lifetime: 40k hr to T70 Panel Reliability: 1:1,000	Efficacy: 90 lm/W Lifetime: 40k hr to T80 Panel Reliability: 1:5,000
Medium (close to user or supporting light) ~300-~2000 lumens 1-10 Panels	Efficacy: 90 lm/W Lifetime: 40k hr to T70 Panel Reliability: 1:10,000	Efficacy: 120 lm/W Lifetime: 40k hr to T80 Panel Reliability: 1:50,000
High (primary illumination) >1500 lumens 5+ Panels	Efficacy: 100 lm/W Lifetime: 40k hr to T70 Panel Reliability: 1:50,000	Efficacy: 150 lm/W Lifetime: 40k hr to T80 Panel Reliability: 1:250,000

DOE Impact on OLED Key Attribute Advances

Past Funding:
2X improvement in Efficacy
3X improvement in Lifetime
1.8X improvement in Light Extraction
40% reduction in Price



Future Funding:
2X additional improvement in Efficacy
2.4X additional improvement in Lifetime
1.4X additional improvement in Light Extraction
80% additional reduction in Price

OLEDWorks
Naturally Illuminating

Conclusions

- Two keys to improving OLED lighting efficacy
  - Increase light extraction from 50-55% to 70%
  - Replace fluorescent blue with stable phosphorescent, TADF or hyperfluorescent blue
- Waveguide mode is main source of lost photons in commercial OLED lighting panels
- Current scattering type light extraction meets most light extraction requirement, but does not extract all waveguided photons
- An advanced light extraction technology is needed to reach 70%
- Efficacies up to 160 lm/W possible if DOE targets for light extraction and blue IQE are achieved
- At 160 lm/W OLED can meet mainstream lighting market requirements for high lumen applications
- DOE support is critical to achieving these goals and to keeping the US as the worldwide leader in OLED lighting