Market Opportunities and Manufacturing Challenges in OLED Lighting

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CCR Workshop
Minneapolis
June 7, 2011

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Introduction to JNB

- MA in mathematics, Cambridge University
- Ph.D. in theoretical physics, University of Manchester
- 20 years as a physics professor, mainly at University of Pittsburgh
- 30 years research in atomic & molecular physics & ionized gases
- 15 years managing research at Lawrence Livermore National Lab
- 15 years as advisor to industry on displays & lighting
- 4 years as consultant to the DOE Solid State Lighting Program

I know a little about a lot of things
but am not an expert on anything

- My major goal is to encourage collaborations
  to bring technology from the lab to market
- I do not make market forecasts or give investment advice

Outline

- **What is the market opportunity?**
  - Form, fit, function and flair
  - Energy savings
  - Light control
- Efficacy – key to long life & low cost
  - Light extraction
  - Voltage reduction
  - Spectrum shaping
- Manufacturing challenges
  - Reliability and reproducibility
  - Cost
  - The valley of death

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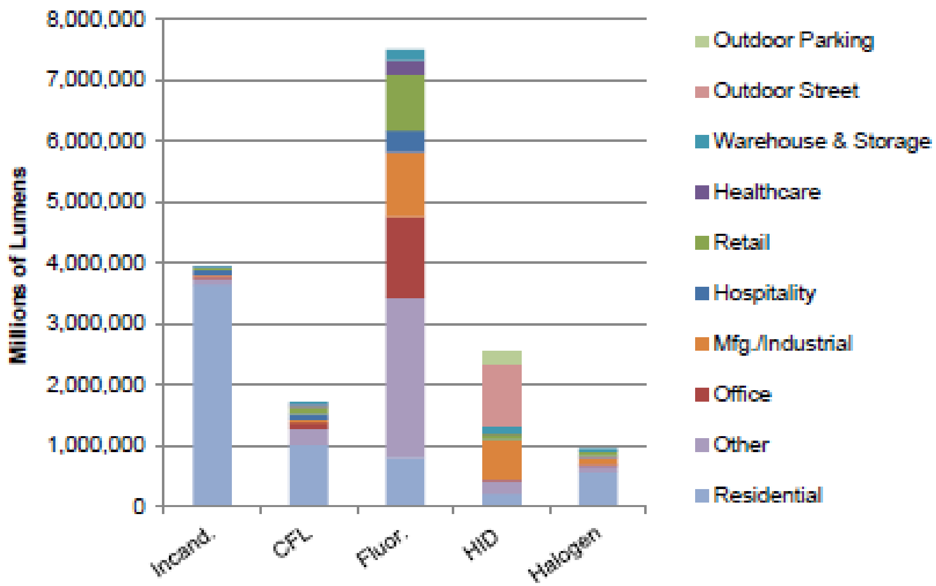
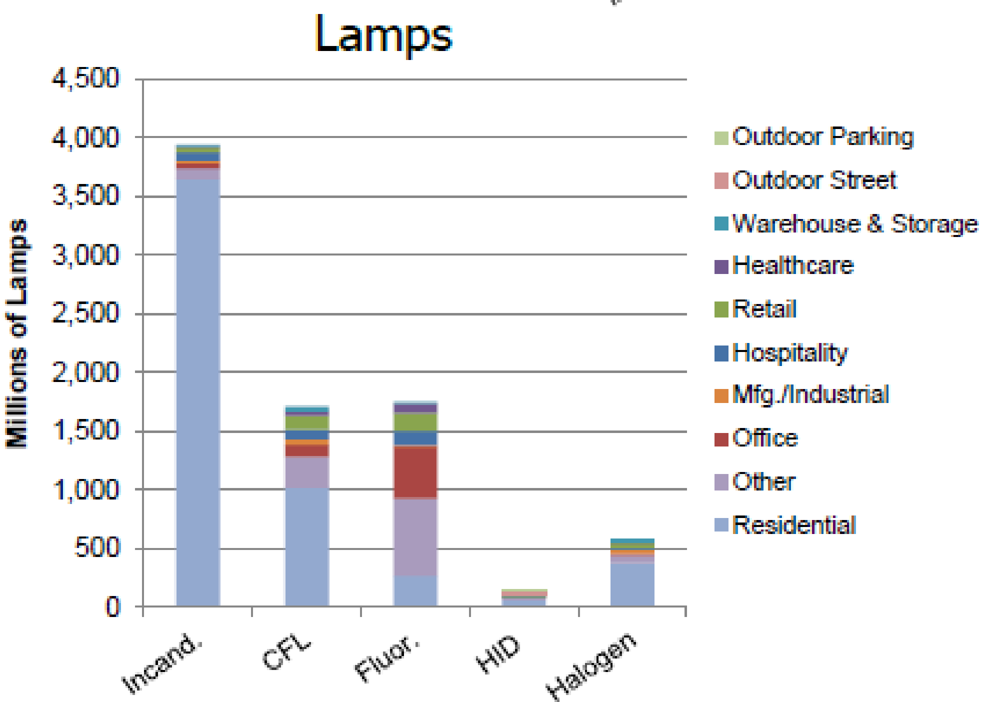
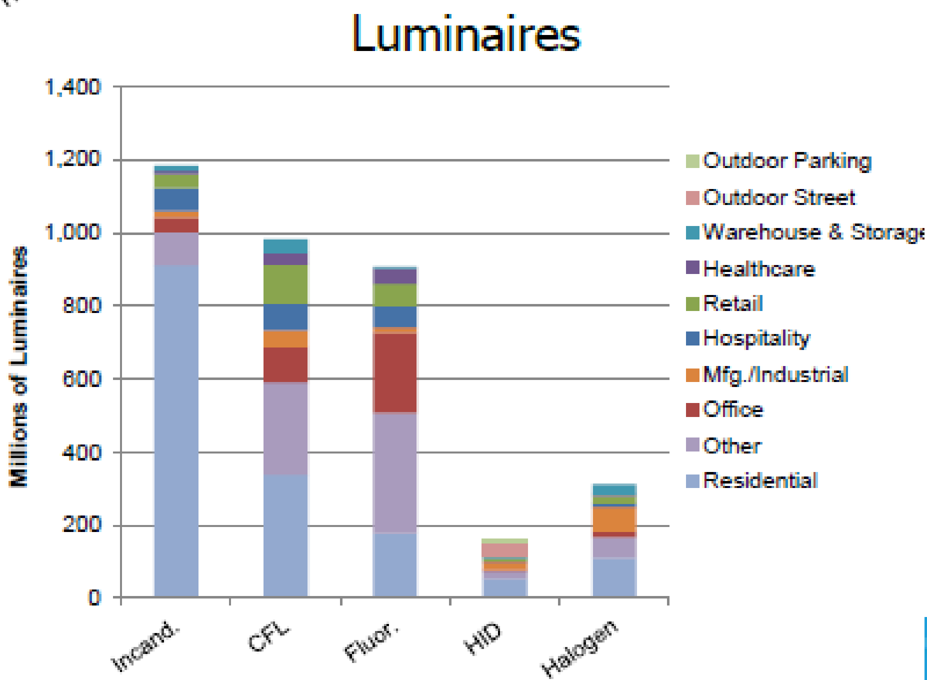
Sizing the NA Market – Lumens, Lamps and Luminaires

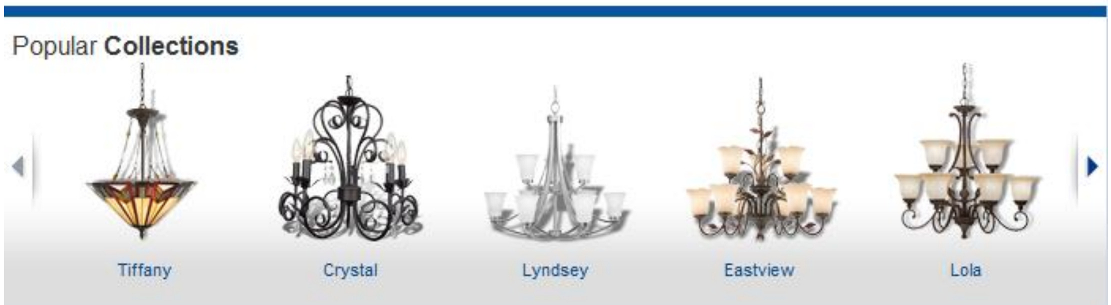
Source: Ross Young IMS Research 2011







Hiding The Light: A Waste of Energy and Money?



Sources: Lowes.com; Lighting Direct.com; Lithonia; Thomas

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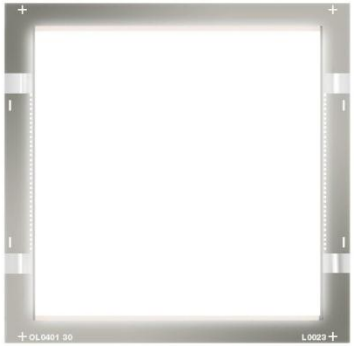
The Best OLED Lighting You Can Buy Today

- Luminous efficacy: 45 lm/W
- Thickness: 1.8 mm
- Lifetime: 10,000 hours
- Luminance: 1,000 cd/m²
- Current/voltage: 71.5 mA / 3.6 V
- Color coordinates (x; y): 0.45 ; 0.41
- Color temperature: 2,800 K



• NEW OFFER •

- Active area: ~ 40cm^2
- Light output: ~12 lm
- Price: $175 (€120)
- Price per kilolumen: ~ $14,500

Manufacturing Priorities: Higher Brightness and Larger Area

Lumiblade Plus from Philips:

https://www.lumiblade-shop.com/

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Mondo on OLED Lighting Design 2010

mondo arc
THE INTERNATIONAL MAGAZINE FOR ARCHITECTURAL RETAIL AND COMMERCIAL LIGHTING

David Morgan: “The audience was non-plussed.
This particular version of the future looks rather boring and flat”

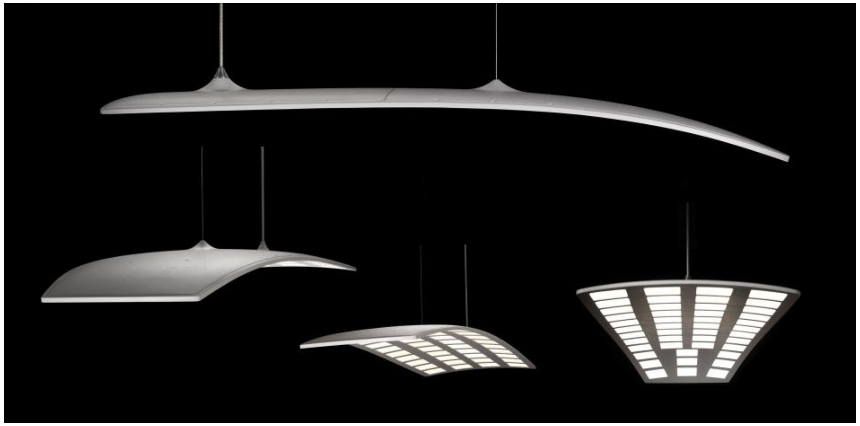
Ingo Maurer: “OLED light has a more spiritual feeling than traditional light sources,
it also has no sex appeal as it is so flat

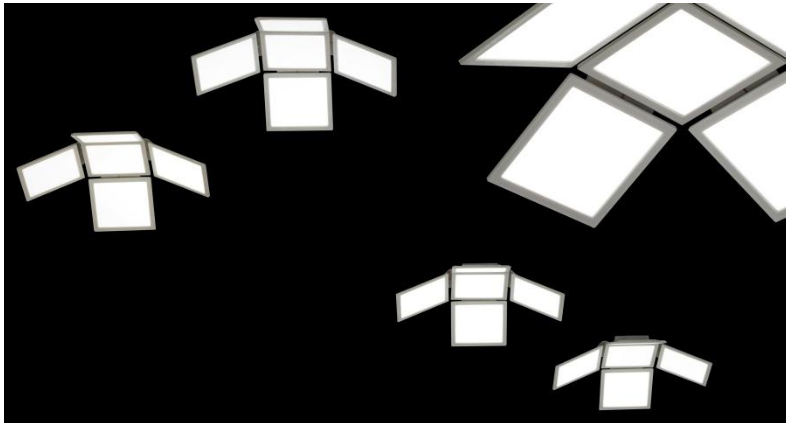
Philippe Starck also finds the quality of light from OLED panels to be boring
and the technology incomprehensible

David Morgan : “The luminaire and OLED manufacturers …. went home disappointed”

http://www.mondoarc.com/comment/guest_articles/561089/our_oled_insider.html

Prototype OLEDs





Acuity

GE

Novaled

UDC-Armstrong

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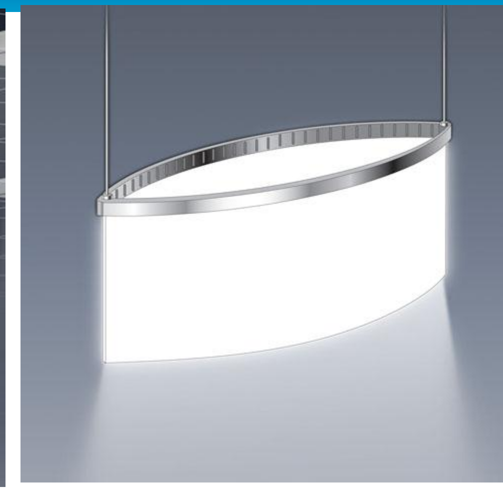
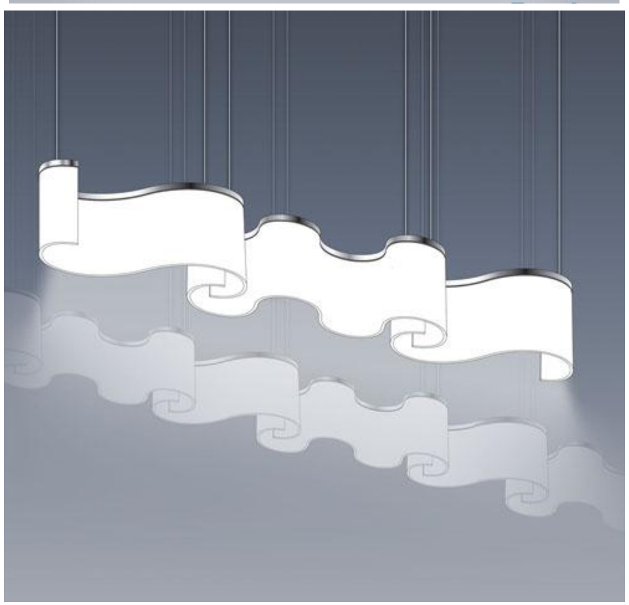
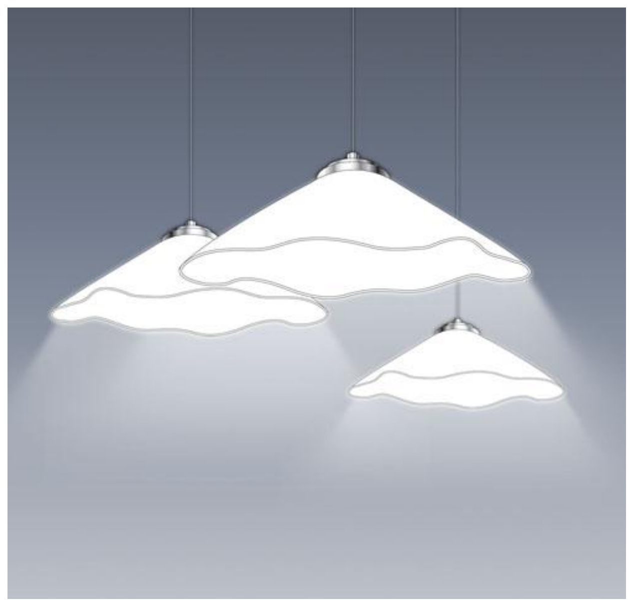
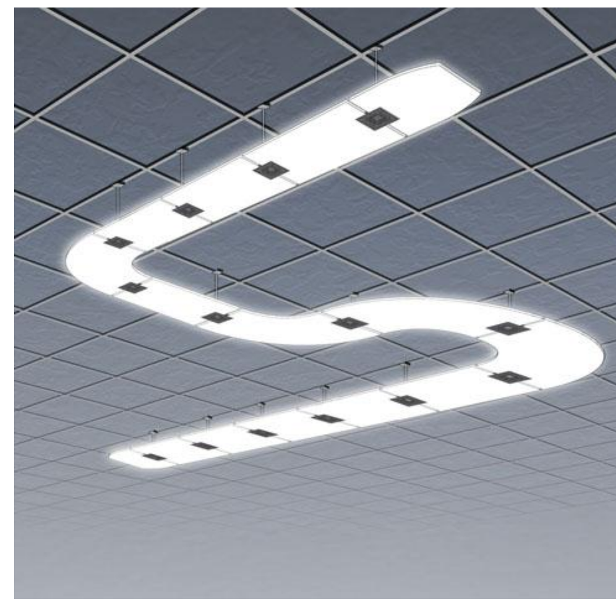
Suspended Ceiling Lights?



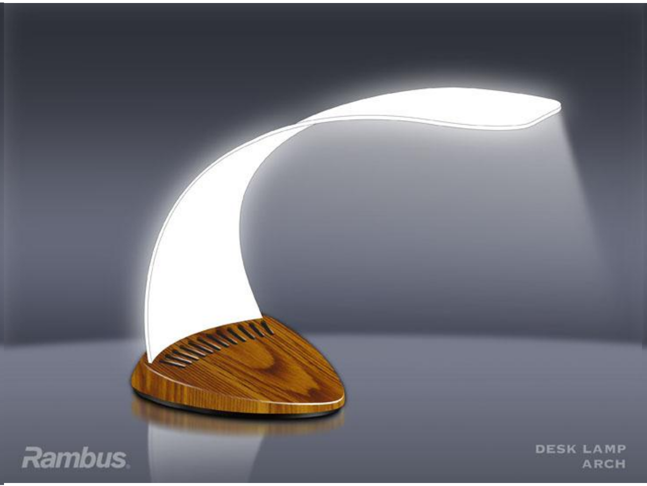


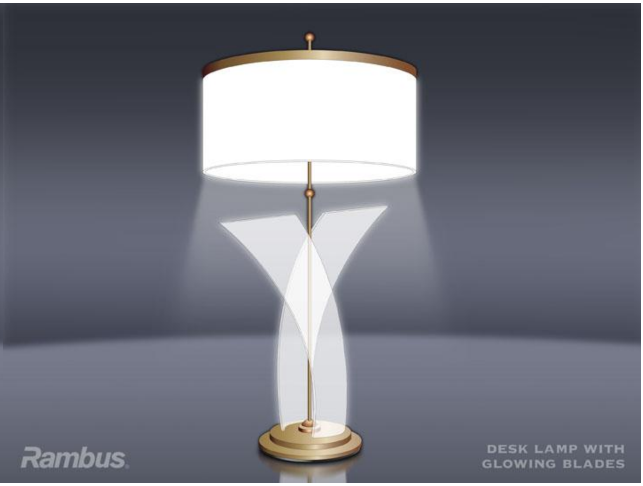




Pentelic Designs from Rambus

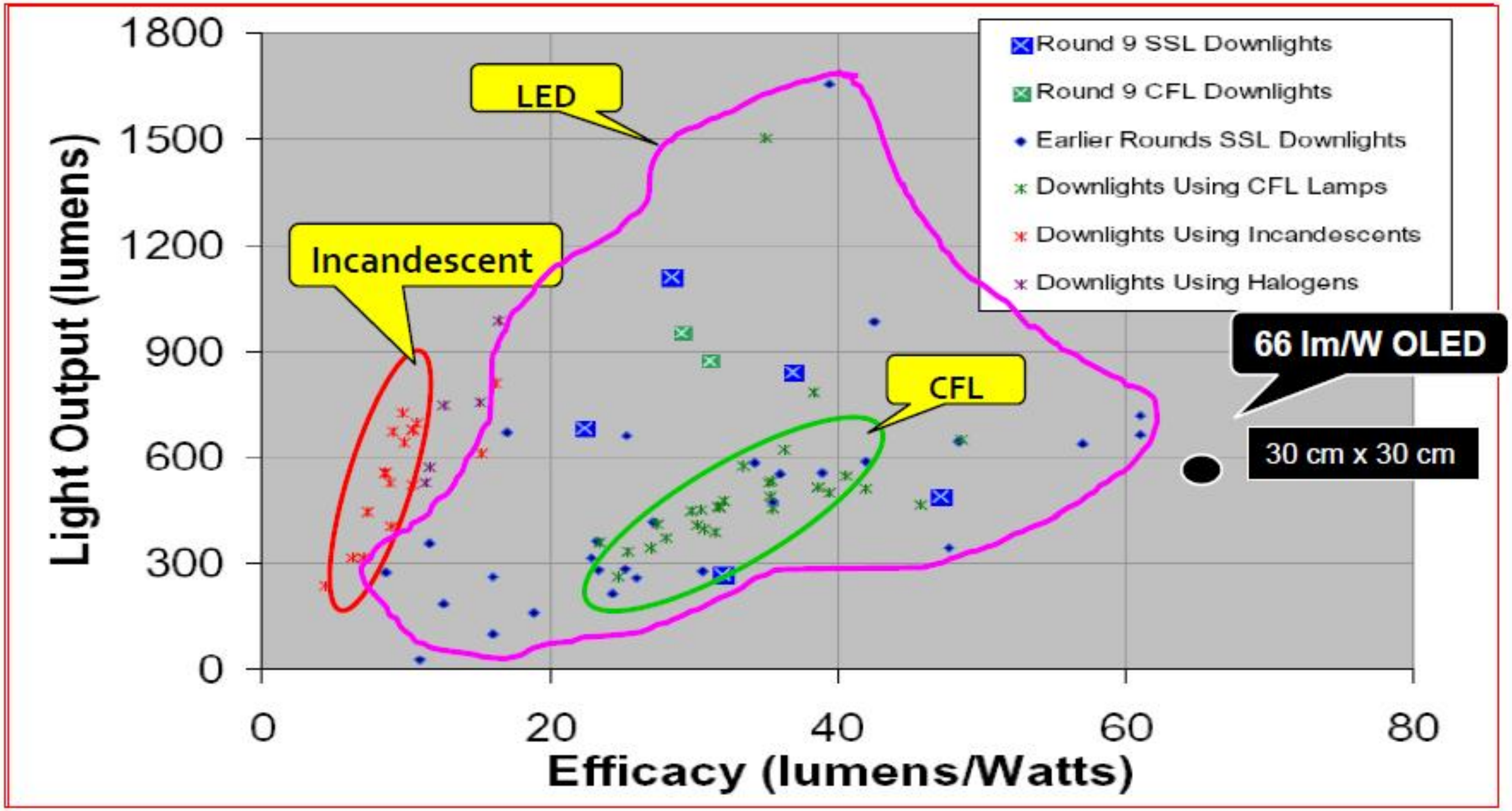
Table or Desk Top Lamps?





Pentelic Designs from Rambus

Is OLED Efficacious Enough?



Source: DOE CALiPER Round 9 Summary Report

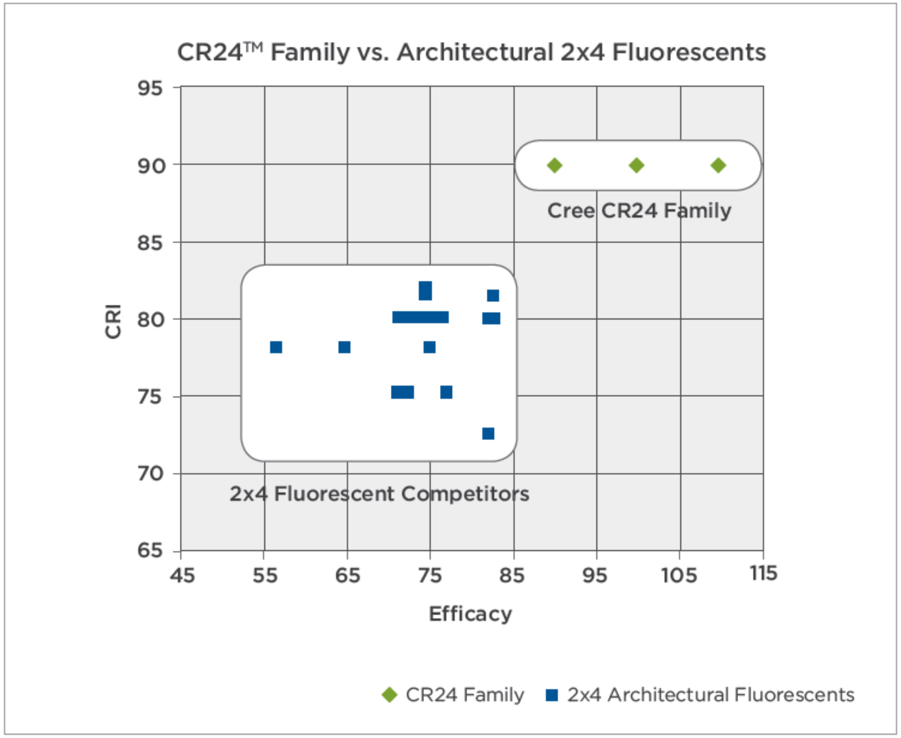
The Goal Posts Are Moving!

Cree CR24™ Troffer

Product Series & Size	Lumen Output	Color Temperature
CR24 2'x4'	**22L** 22W 2200 Lumen - 100 LPW **40L** 44W 4000 Lumen - 90 LPW **40L HE** 36W 4000 Lumen - 110 LPW **50L** 50W 5000 Lumen - 100 LPW	**35K** 3500 Kelvin **40K** 4000 Kelvin

50,000 hour lifetime

5-year warranty



Price: $200-300
CR24-40L35K

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Super T8s are efficient

1. Lamp + ballasts = 100 lumens per watt
2. They achieve this at 3500 K &> 80 CRI
3. Lamp + ballast + luminaire = 80 to 90 lumens / watt
4. Correctly applied high quality, ambient light in the office needs only .45 to .55 watts / sq ft
5. Dimming and controls have been shown to reduce that to .25 to .35 watts / sq ft. actual, measured load
6. If SSL can make luminaires twice as efficient, the energy savings would be about .1 to .2 watts / sq ft
7. At 80 sq ft / luminaire, .2 watts savings = $10.48 / yr

(80 x .2 x 14 hrs/day x 312 days/yr x $.15 /kwhr 1,000)

Source: Terry Clark (Finelite) DOE SSL R&D workshop 2011

OLED Luminaire Efficacy Targets

Metric	2010	2012	2015	2020
Panel Efficacy (lm/W)	58	86	125	168
Optical Efficiency of Luminaire	100%	100%	90%	95%
Efficiency of Driver	88%	90%	93%	93%
Total Efficiency from Device to Luminaire	88%	90%	84%	88%
Luminaire emittance (lm/m^2)	3,000	6,000	9,000	9,500
Resulting Luminaire Efficacy (lm/W)	51	77	105	148

Note: Efficacy projections assume CRI > 80, CCT 2580-3710
The values of optical efficiency quoted for 2010 and 2012 assume no light shaping optics

DOE SSL R&D Multi-Year Program Plan, March 2011
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2011_web.pdf

(I)LED Luminaire Performance Targets

Metric	2010	2012	2015	2020
Package Efficacy – Commercial Warm White (lm/W, 25°C)	92	141	202	266
Thermal Efficiency	86%	86%	88%	90%
Efficiency of Driver	85%	86%	89%	92%
Efficiency of Fixture	85%	86%	89%	92%
Resultant luminaire efficiency	62%	64%	69%	76%
Luminaire Efficacy – Commercial Warm White (lm/W)	57	91	139	202
High Current Luminaire Efficacy – Commercial Warm White (lm/W)	44	74	123	202

Notes:

1. Efficacy projections for warm white luminaires assume CCT=2580-3710K and CRI=80-90.
2. All projections assume a drive current density of 35 A/cm^2, reasonable package life and operating temperature.
3. Luminaire efficacies are obtained by multiplying the resultant luminaire efficiency by the package efficacy values.

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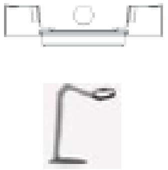
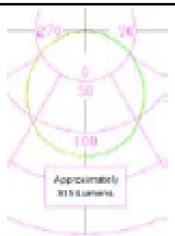
DOE SSL R&D Multi-Year Program Plan, May 2011

Application Efficiency: Office Lighting

Source: Acuity Lighting(2011)

Lighting System Type	Approx W/sf	Excessive Non-task, Circulation Illumination	Application Efficiency
 2x4 LED Advanced Troffer	0.62	6X, 8X	35%
 Fluorescent Low Ambient with LED Task	0.56 – 0.69	4X, 5X	36-44%

Lighting System Type	Approx W/sf	Excessive Non-task, Circulation Illumination	Application Efficiency
 Clustered OLED Tiles	0.47 (100 lm/w) 0.78 (60 lm/w)	4X, 3X	52%

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Jeannine Fisher, Peter Ngai, and Min-Hao Michael Lu
Int. Display Manufacturing Conf., paper 23-01

LUNERA™

(I)LED @ 50-60lm/W vs fluorescent in large office

Limited focusing: 66% of Lambertian at 75^{0}

OFFICE ENVIRONMENT

LUNERA	FLUORESCENT
Lunera LED 2200 (55W)	3 Lamp T8 (89W)
10' x 10' spacing	10' x 10' spacing

LIGHTING SCENARIO

Project Type: Retrofit

Facility Type: Standard Open Office

Building Size: 100,000 sq/ft office

Electricity Cost: $0.135/kWhr (5% appreciation for inflation)

Duty Cycle: 12/5 — 3,120 hours/yr

Ceiling Height: 12 ft

COMPARATIVE ANALYSIS

	LUNERA	FLUORESCENT
AVERAGE KWH* CONSUMED/YR	145,860	302,640
FIXTURES REQUIRED	1,000	1,000
LIGHTING POWER DENSITY (LPD)	0.55 W / SQ FT	0.89 W / SQ FT
GREEN HOUSE GAS (5 YEARS)	627 TONS	1,301 TONS

Payback
↓3.1 YEARS

Lifecycle Savings
↓$1,095,000

kWhr Saved Annually
↑156,780

Lamp Life Improvement*
↑2X

Electricity & Maintenance Cost Reduction
↓72%

Uniformity Improvement
↑2x

Tons of CO2 (over 5 years)
↓674

*Lunera solution includes dimming controls.

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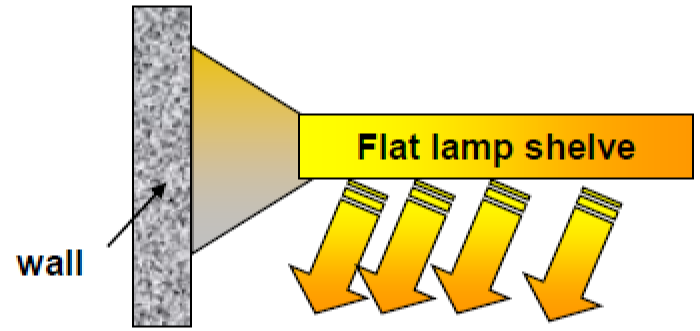
Shop: Shelves and integration in furniture

Product Description:

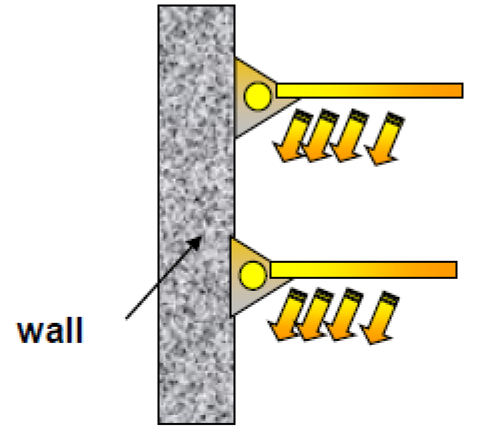
Self-illuminated shelves, self-illuminated backwalls for effective presentation of goods



Lamp specification:

Single side / double side

Luminance	1,000 cd/m²
Light output	2,500/5000 lm/m²
Efficiency	>40 lm/W
Typical size	0.3 x 1.0 m 0.6 x 1.0 m



Source: Jorg Amelung

Combine Markets to Achieve Scale

Application	Est. Market (m^2)	Cost Limit ($\$/m^2$)
General Area Lighting	5,000,000+	$100
Flexible	200,000	$200
Transparent	100,000	$300
Ultra thin/ light weight	200,000	$400
High Performance (l/m2)	100,000	$500
Architectural	100,000	$700

Must Validate

Separately niche applications will never hit the cost targets due to low manufacturing volumes.

If multiple niche applications can be done on the same production line, then reasonable costs can be achieved.

Source: David Gotthold

Veeco

Home Depot Lighting Fixtures by Price

Price ($)	Ceiling Mounts	Decorative Fluorescents	Pendants	Chandeliers
0-200	901	267	996	468
200-400	94	17	278	477
400-600	19	3	78	173
600-800	4	0	36	81
800-1000	3	0	12	30
1000-2000	11	0	36	75
2000-4000	1	0	8	24
4000-11,000	0	0	7	9
Total	1033	287	1325	1323
Energy Star Qualified	**163**	**239**	**124**	**121**

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http://www.homedepot.com/

Outline

- What is the market opportunity?
  - Form, fit, function and flair
  - Energy savings
  - Light control
- **Efficacy – key to long life & low cost?**
  - Light extraction
  - Voltage reduction
  - Spectrum shaping
- Manufacturing challenges
  - Reliability and reproducibility
  - Cost
  - The valley of death

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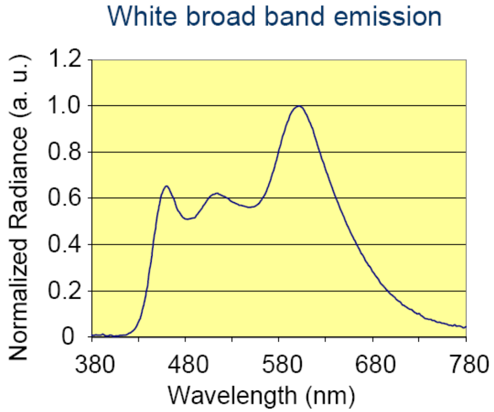
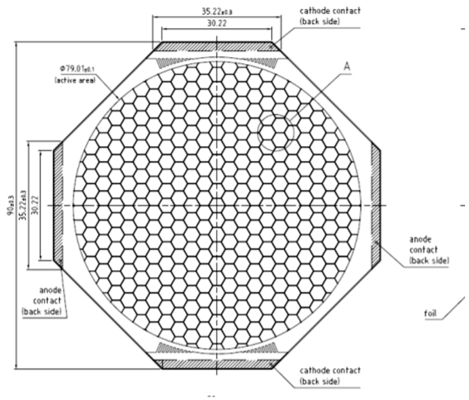
Efficacy – Factors

- Luminous Efficacy of Radiation
  - Increase from 325 lm/W to ~400 lm/W
  - Narrower red emission spectrum
- Internal Quantum Efficiency
  - Need reliable measure
  - Should emitters be all phosphorescent?
- Electrical Efficiency
  - Now ~ 60% on small panels
  - Need 80% on large panels (drive voltage < 2.8V)
- Extraction Efficiency
  - Only ~25% in prototypes
  - 5-year target 60-75%





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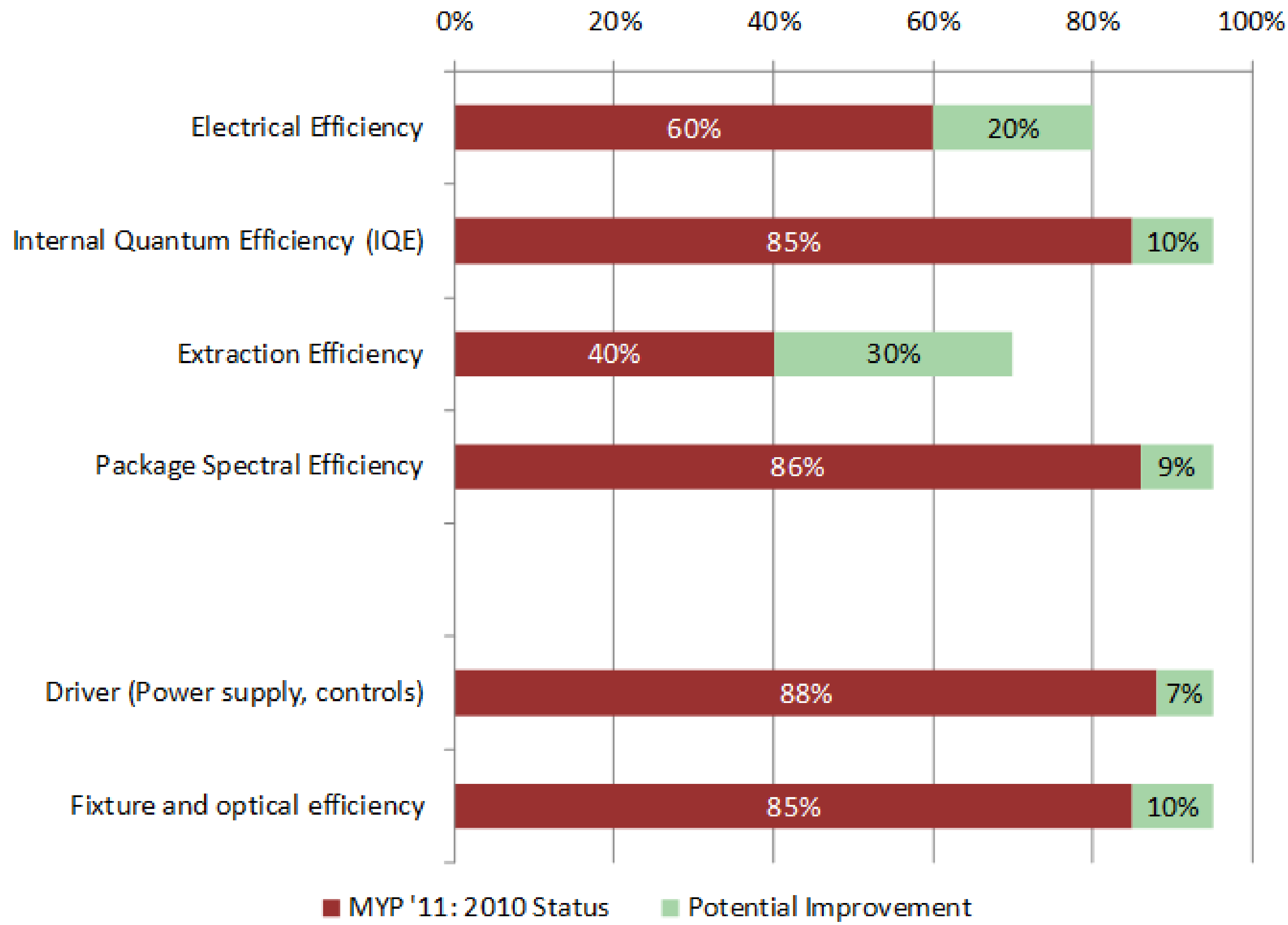
OLED Efficiency Analysis



DOE SSL R&D Multi-Year Program Plan, March 2011

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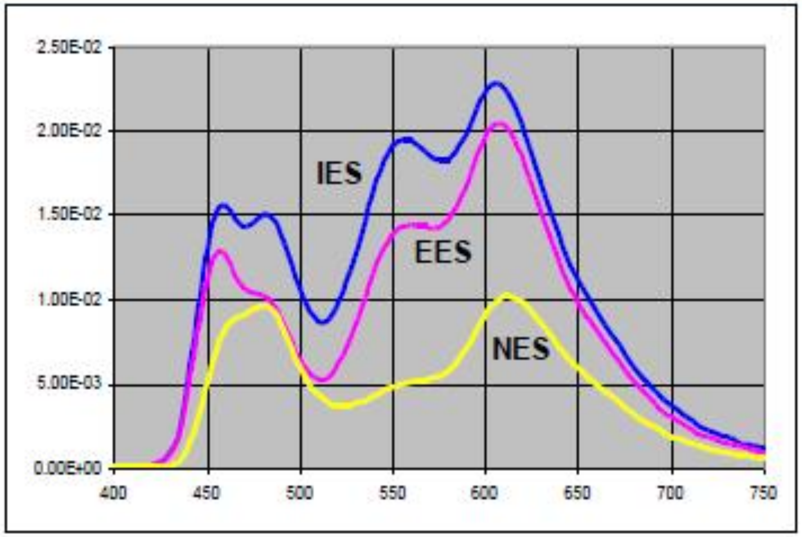
Improved Light Extraction is Critical

Should be accomplished through thin-film structures

- Where?
  - Outer surface of transparent substrate
  - Between substrate and transparent conductor
  - Inside transparent conductor
  - Between the electrodes
  - At edges
- How?
  - Scatter light
  - Bend light rays (without chromatic aberrations)
  - Micro-cavities or multi-layers (without chromatic aberrations)
- Uncertainties
  - **Low-cost high-index substrates**
  - **Energy losses in metal electrode**
  - **Manufacturability of sub-micron patterns**
  - **Complementarity of partial solutions**

Kodak Work on Scattering Layers

Tandem Hybrid OLED with IES



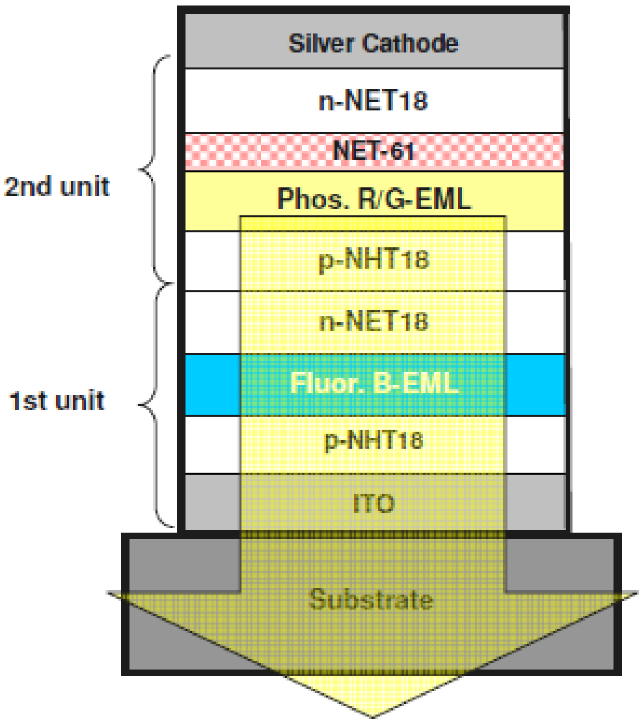
	NES	EES	IES
mA/cm2	1	1	1
cd/m2	430	937	1213
EQE%	23.8	43.9	54.8
cd/A	43.0	93.7	121.3
CIE-x	0.385	0.411	0.393
CIE-y	0.342	0.374	0.387
Voltage	5.9	5.9	5.7
lm/W	23.1	50.1	66.4
CCT,K			3691
dC			0.00145
CRI			84.9
Ratio to NES		2.2	2.9

	Calculated IQE, %	
	If Extration η=60.4%	If Extration η=37.8%
NES 23.8% EQE	91.5	146.5
EES 43.9% EQE	93.8	150.1
IES 54.8% EQE	90.7	145.2

Devices with same layer structure.

Tyan et al SID2009

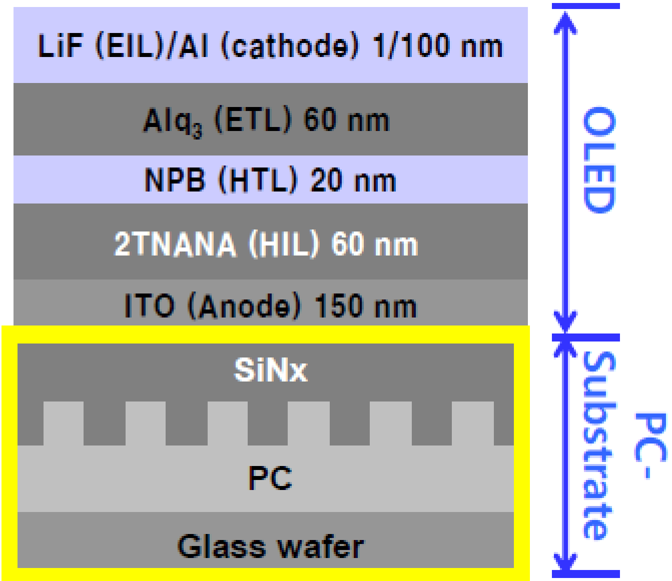
NET-61 Outcoupling in Highly Efficient Tandem OLED

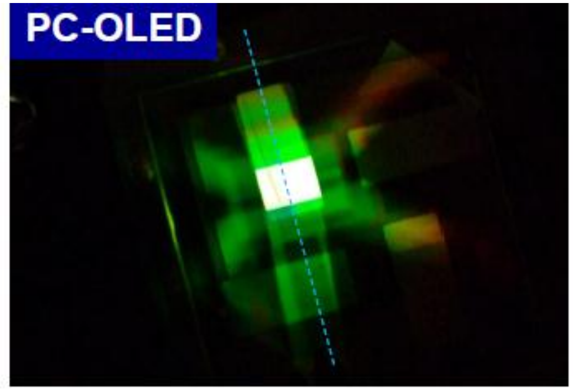


- Two unit hybrid white approach, using fluorescent blue emitters
- Power efficiency of plain OLED is increased from 26.9 lm/W to 38.5 lm/W
- With an external MLA film the power efficiency goes up to **50.1 lm/W @1000 cd/m²** (+ 80% quantum efficiency compared to plain OLED)

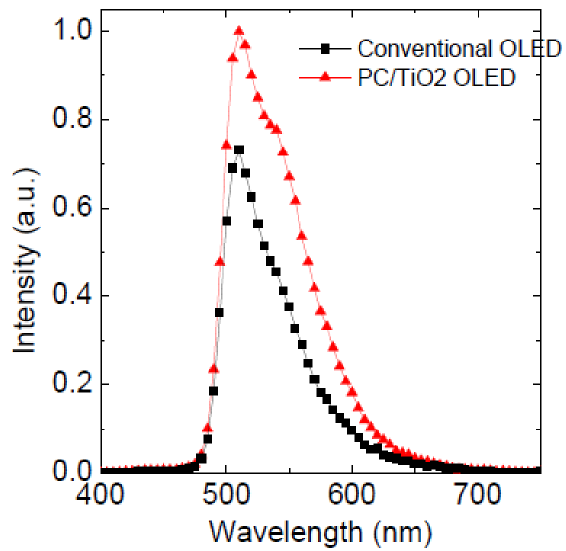
Source: Qiang Huang (Novaled)

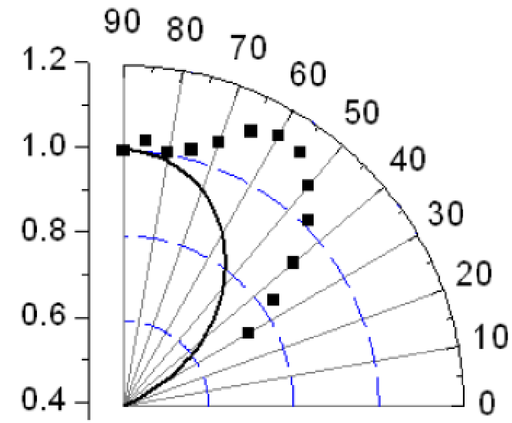
Photonic Crystals by Nano-Imprint Lithography





Integrated intensity and emission pattern





Source: Jan-Joon Kim
Seoul National University

Enhancement by 58%

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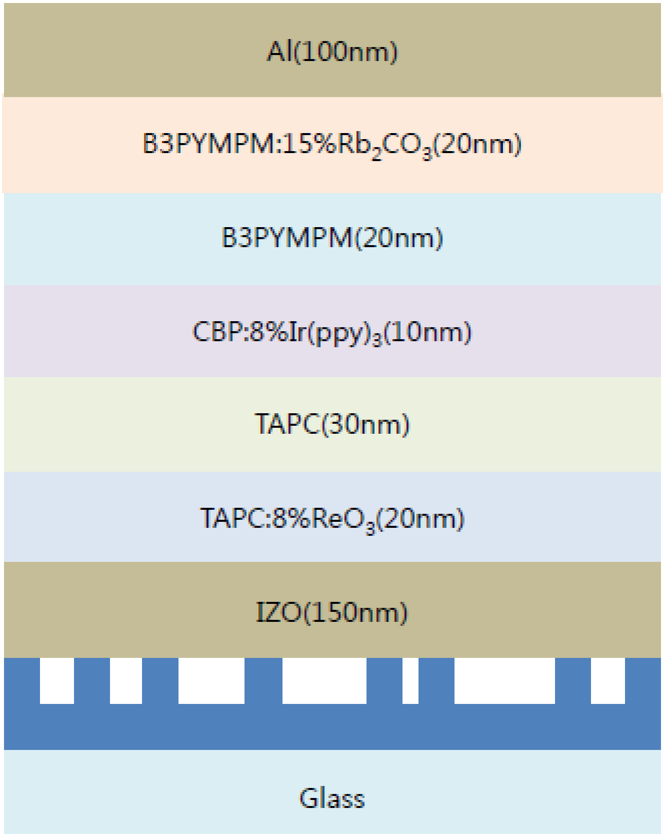
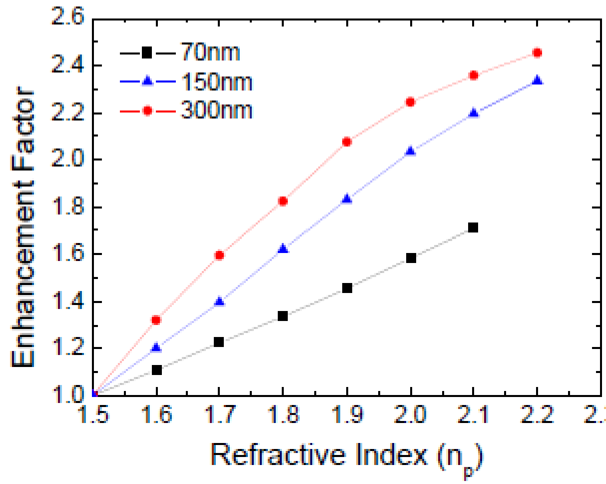
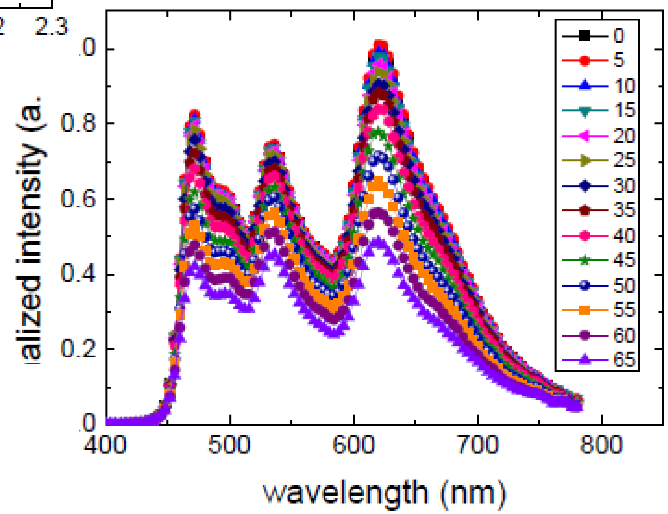
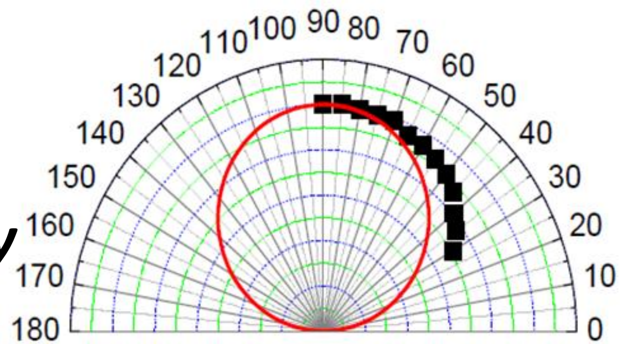
Randomly Dispersed Nano-pillar Arrays









Source: Jan-Joon Kim

Seoul National University

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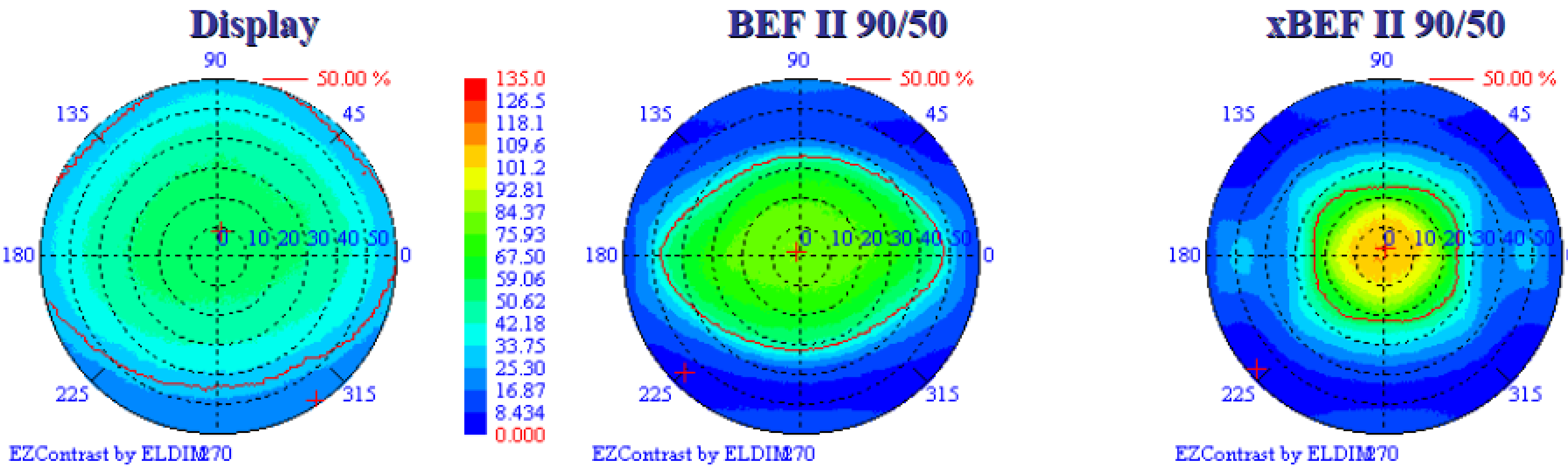
External Control of Light Direction

Vikuiti™ films from 3M



Display	BEF II 90/50	xBEF II 90/50
On-Axis Brightness: 55.27 nits	On-Axis Brightness: 83.10 nits	On-Axis Brightness: 108.7 nits
Brightness Gain: 1.0	Brightness Gain: 1.50	Brightness Gain: 1.97
Hor. 1/2 Brightness Angle: 60.0°	Hor. 1/2 Brightness Angle: 47.0°	Hor. 1/2 Brightness Angle: 24.0°
Ver. 1/2 Brightness Angle: 55.0°	Ver. 1/2 Brightness Angle: 32.5°	Ver. 1/2 Brightness Angle: 23.0°
Integrated Intensity: 105.62 lm/m²	Integrated Intensity: 103.2 lm/m²	Integrated Intensity: 85.57 lm/m²
	2% loss	20% loss

But how do these films interact with the underlying layers?

Source: Bob Bennett (3M)

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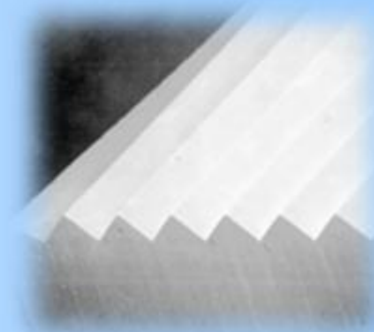
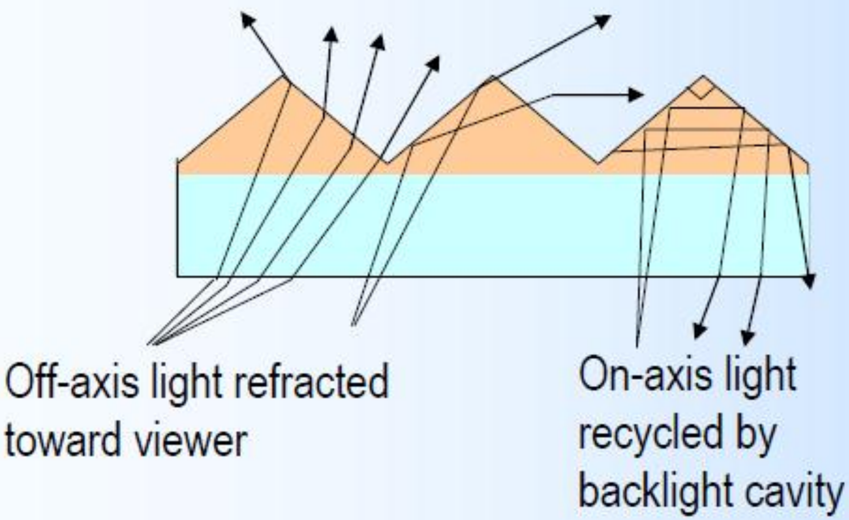
Prism Films Functionality

- **Light is managed geometrically and optimized for the desired use.**
- **Recycles off-axis light not normally useable to the viewer**
- **Improves brightness, contrast, and uniformity**

Vikuiti™ BEF





Vikuiti™ Display Enhancement 3M

Electrical Efficiency

- Efficient transport of current across the panel
  - Transparent conductor
  - Wire grids, bus bars or series connectors

- Injection and transport of charge between the electrodes
  - Electrode work function
  - Transport layers
  - Hosts for dopants in emission layers

- Efficient conversion of energy from electrons to photons
  - Loss to vibrational motion
  - Stokes shifts leading to extra losses for green and red

Target: Reduce the drive voltage to ~2.8V for currents of 2.5 mA/cm^2

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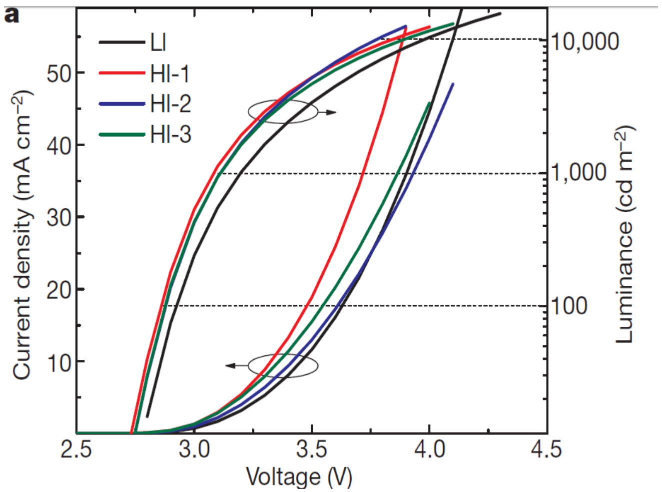
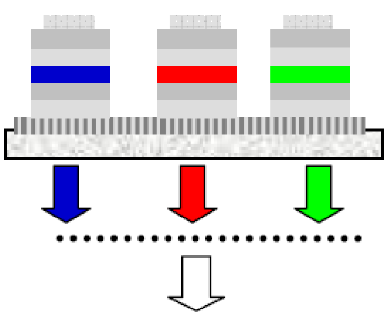
Voltage Reduction Strategies

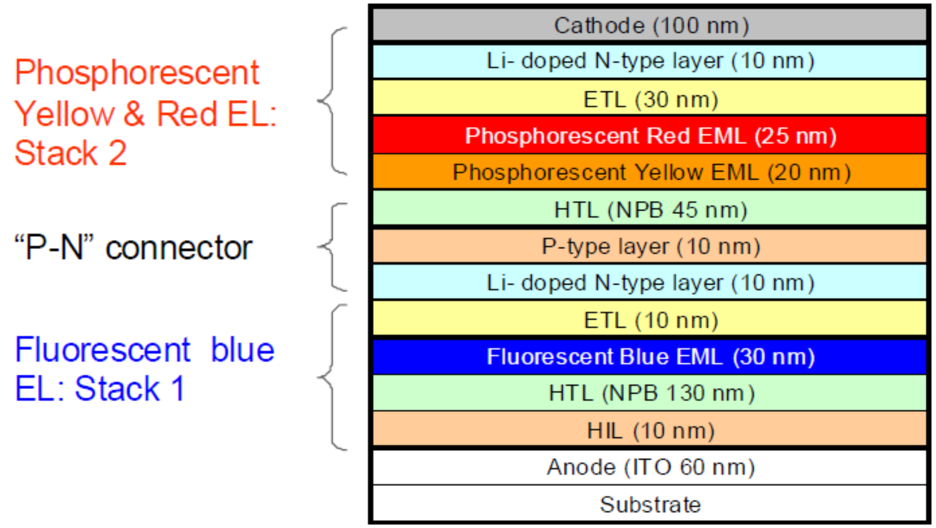


Novaled has shown that **ion-doping** can increase the conductivity of the transport layers
Reineke at al (**IAPP Dresden** 2009)

Color Stripes with Separate Drive (UDC)



Tandem Structures (Kodak)



	mA/cm2	cd/m2	EQE%	cd/A	CIE-x	CIE-y	V	lm/W	CCT	CRI	EQE/NESD
NESD	1	453	21.5	45.3	0.380	0.392	5.7	24.8			
EESD	1	795	37.0	79.5	0.383	0.378	5.7	43.9	3865	81.1	1.72
IESD	1	1022	49.2	102.2	0.387	0.389	5.7	56.0	3836	83.6	2.29

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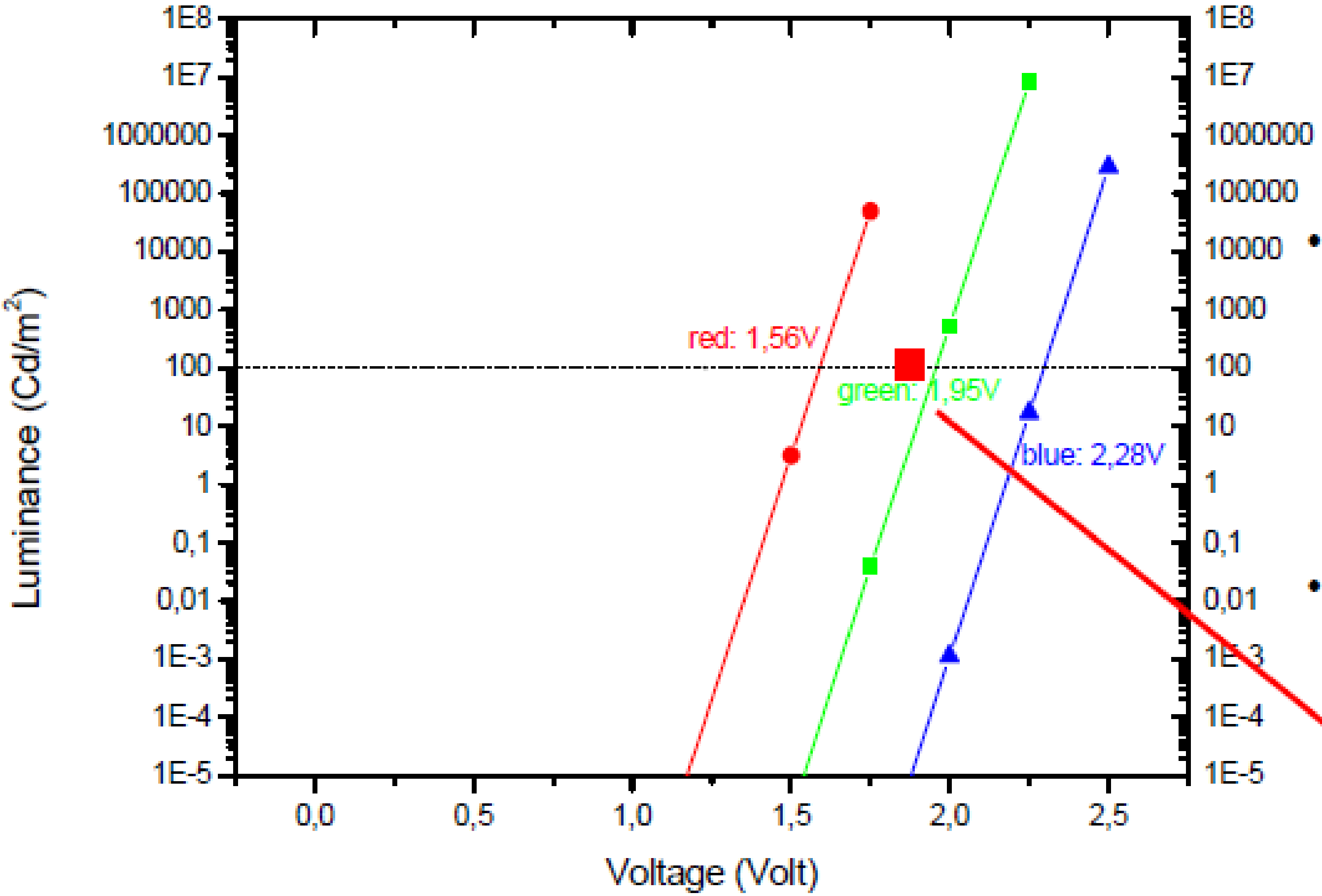
Where ist the voltage limit: Results for thermodynamically ideal device

Source: Karl Leo (IAPP Dresden)



- At 100Cd/m^2: only about 20% excess voltage over theoretical limit
- Voltages at high brightness can still be improved!

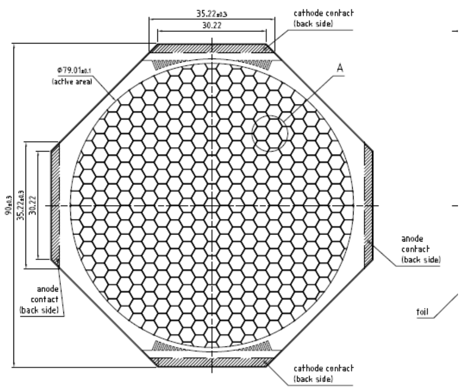
R. Meerheim et al., Proc. SPIE 6192, 61920P/1 (2006)

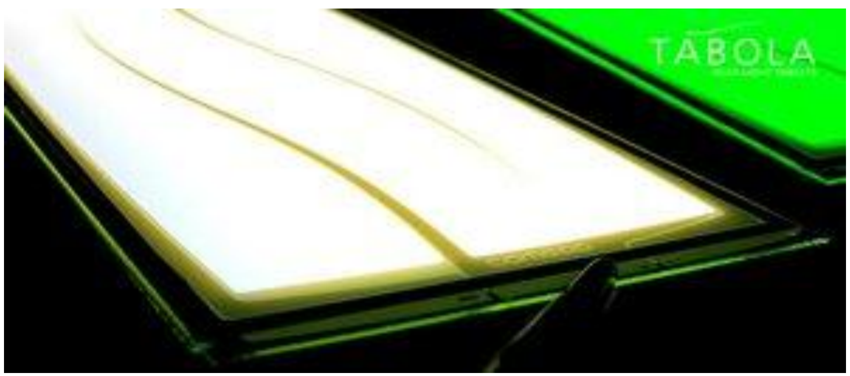
Best value for red: 1.89V (Novaled)

Transparent Conductors and Metal Grids

Voltage drop across panel should be less than 0.03V

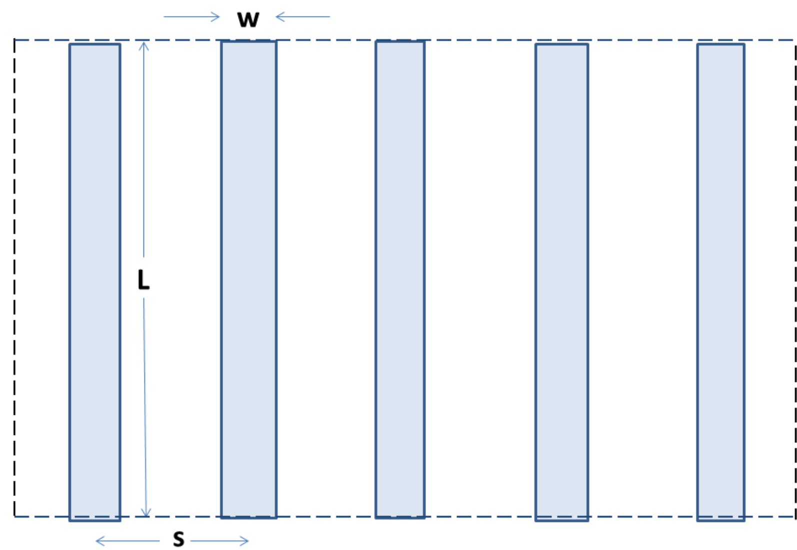
Hexagonal grids in Orbeos from Osram





Tabola from Fraunhofer IPMS

Parallel metal bars driven from both ends



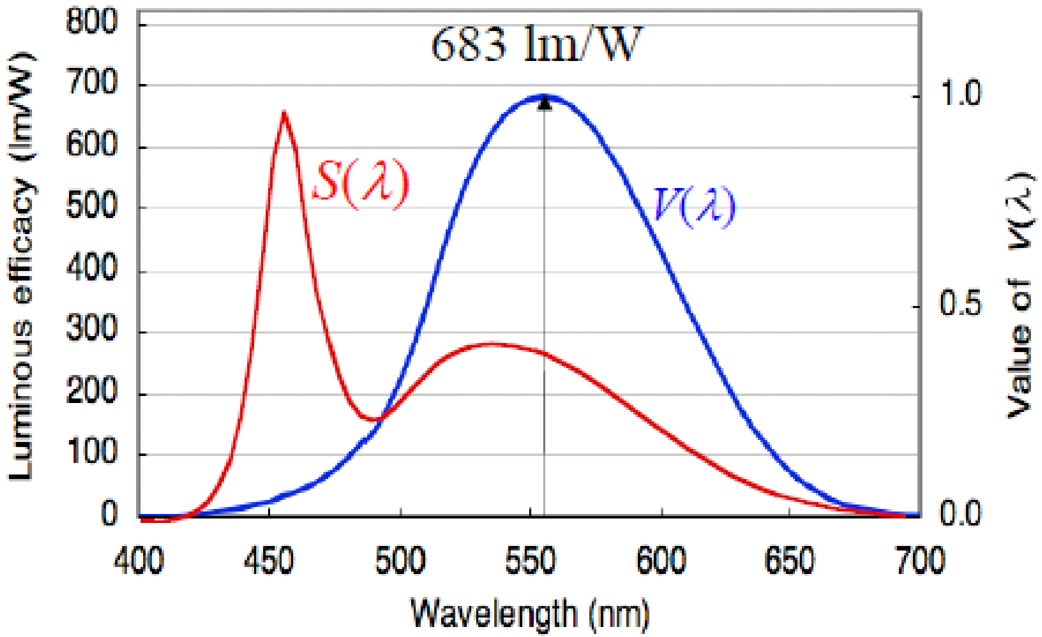
For acceptable light blockage w/s < 0.1

For bulk Al wires and good ITO
L can be up to ~ 20 cm
s can be up to ~ 2 cm

IR losses are minimal

Luminous Efficacy of Radiation (lm/W)

Theoretical lm/W for a given spectrum



$$K = \frac{K_m \int_\lambda S(\lambda) V(\lambda) d\lambda}{\int_\lambda S(\lambda) d\lambda} \quad [lm/W]$$

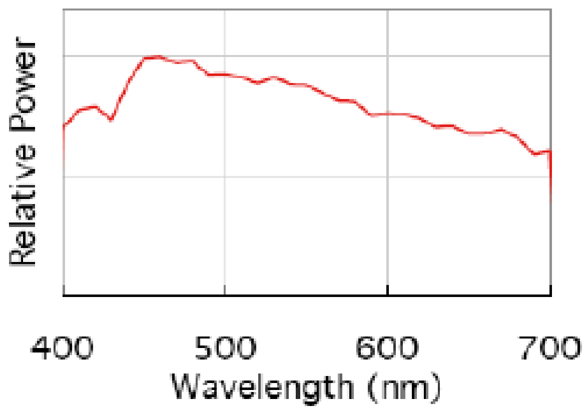
$$(K_m = 683 \text{ lm/W})$$

<Examples of LER>

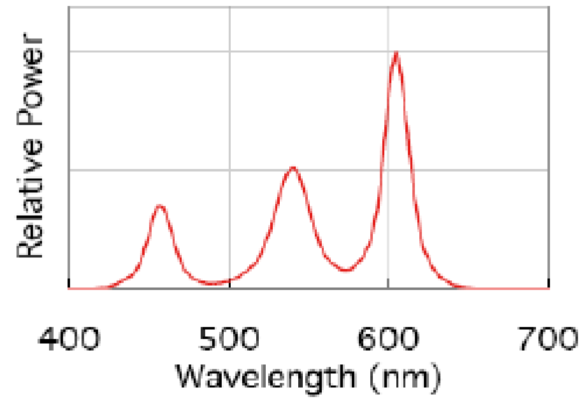
Tri-p FL (3300 K)	~350 lm/W
CW FL (4300 K)	~340 lm/W
MH (4300 K)	~300 lm/W
HPS (2100 K)	~380 lm/W
OLED (3000 K)	**~325lm/W**

Light Spectra and Color Quality

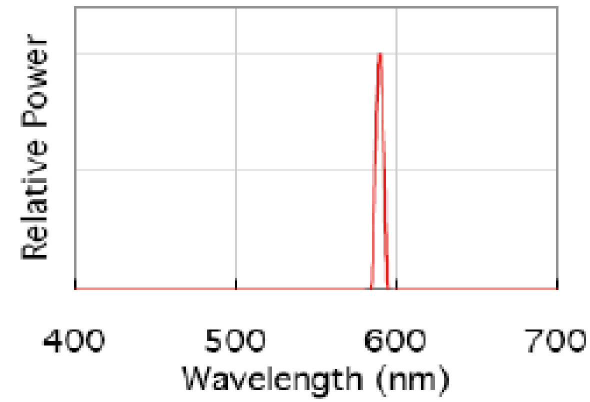
Daylight



White LED



Low pressure sodium lamp



LER (theoretical maximum)

~250 lm/W | ~ 400 lm/W | 520 lm/W

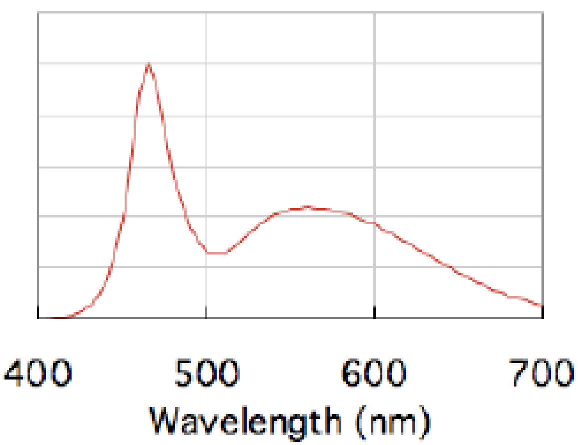
Excellent color rendering | ?? color rendering | No color rendering

Phosphor white LED simulation

Ph-LED YAG

CCT: 6814
Duv: 0.004
CRI Ra: 81
R9: 24

LER (lm/W): 294
CQS 78

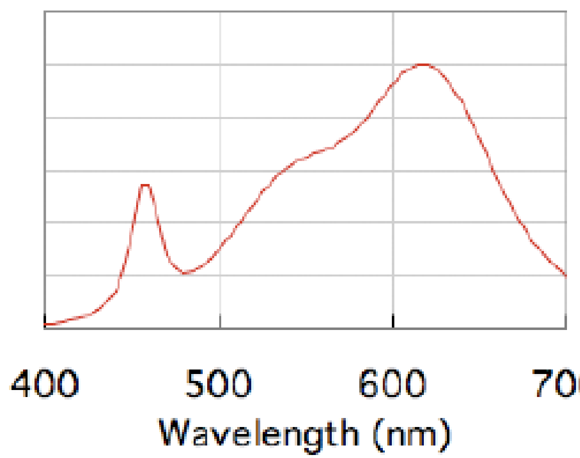


Red phosphor solution

3-LED model

CCT: 3000
Duv: 0.000
CRI Ra: 90
R9: 45

LER (lm/W): 310
CQS 89

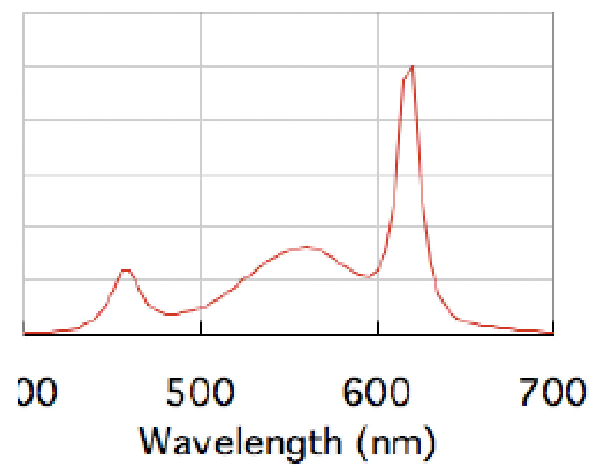


Red LED peak solution

3-LED model

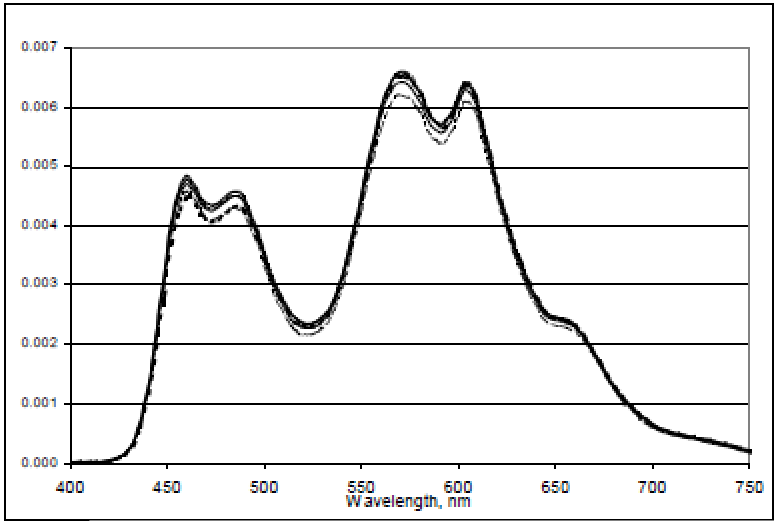
CCT: 3000
Duv: 0.000
CRI Ra: 90
R9: 30

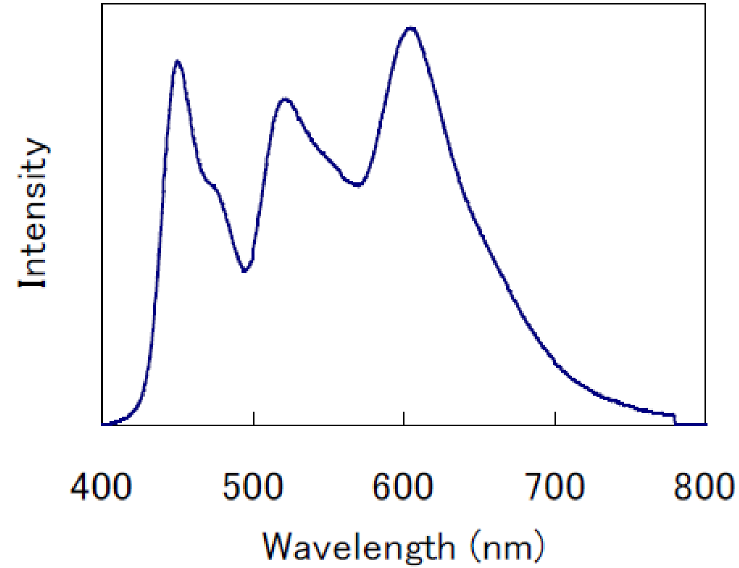
LER (lm/W): 375
CQS 86



OLED Spectra

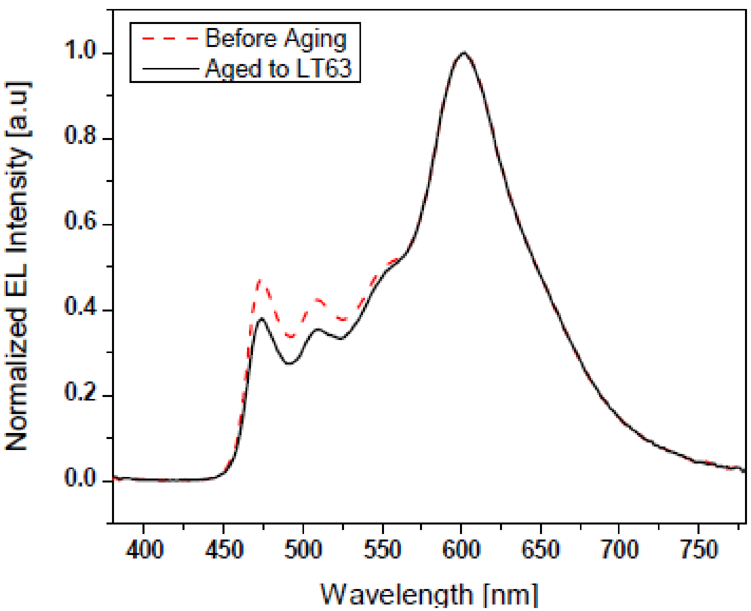
Kodak 2008

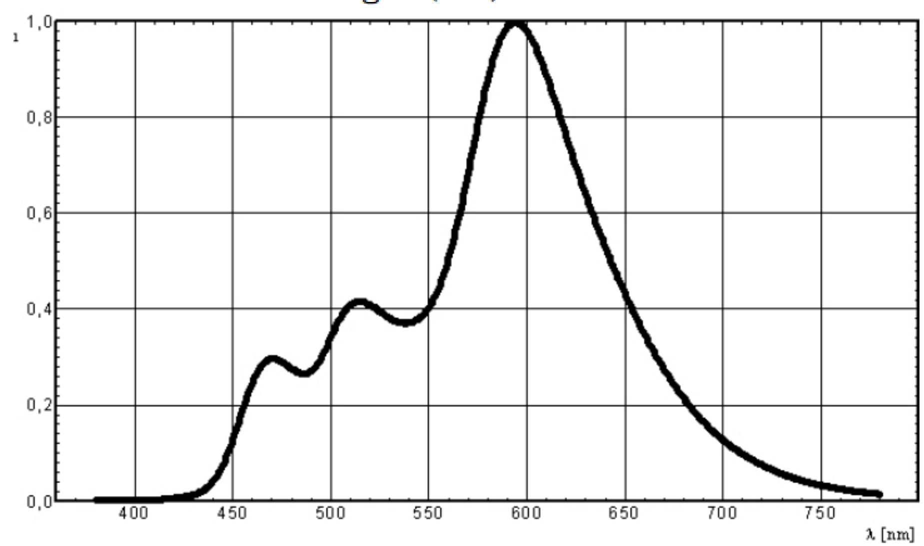




Panasonic 2011

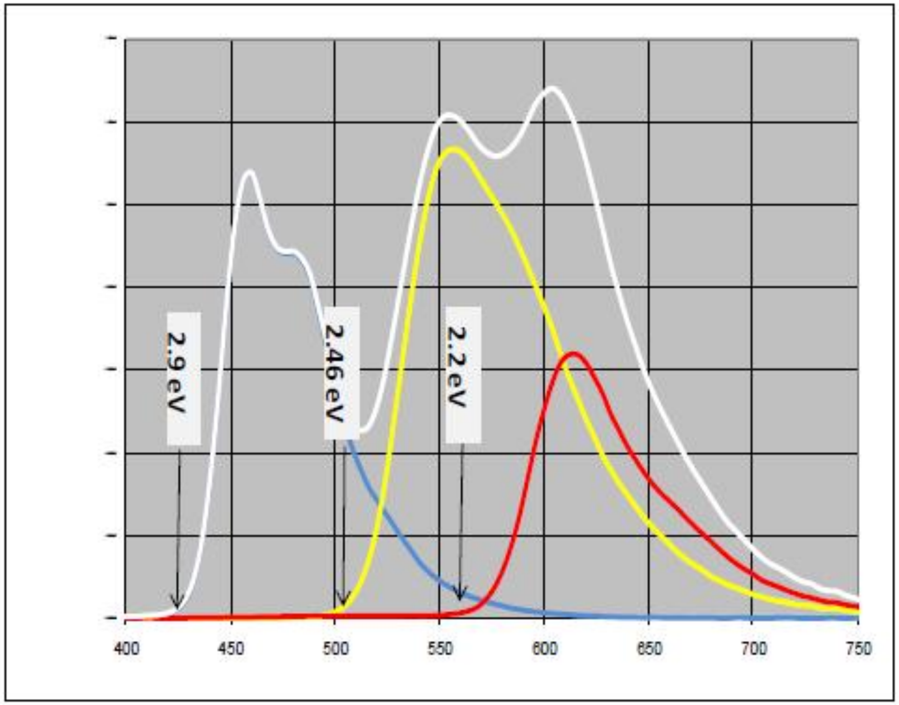
UDC 2010





Osram Orbeos 2010

OLED Efficacy : Theoretical Limit



	Phosphorescent Single Stack	Hybrid Double Stack
CCT =	4000 K	4000 K
	Model	Model
B	26.6	36.2
G	49.3	66.7
R	24.1	33.3
IQE	100%	136%
Lum/A	721.7	984.8
Voltage	2.9	5.4
Extrct	100%	100%
EQE	100%	136%
LPW	249	184

Outline

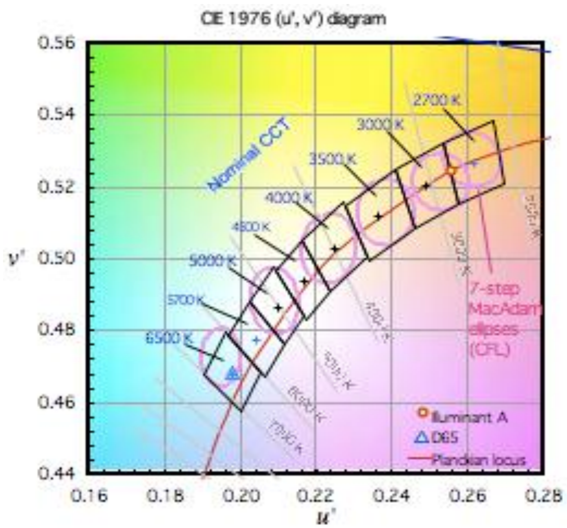
- What is the market opportunity?
  - Form, fit, function and flair
  - Energy savings
  - Light control
- Efficacy – key to long life & low cost
  - Light extraction
  - Voltage reduction
  - Spectrum shaping
- **Manufacturing challenges**
  - Reliability and reproducibility
  - Cost
  - The valley of death

Manufacturing Issues

- Best manufacturing strategy is still unclear
  - Sheet vs roll-to-roll
  - Dry vs wet processing
  - Rigid versus flexible substrates
  - Simple vs complex structures
- Various options for the manufacturing scale
  - Desk-top style printing (eg AVI)
  - Gen 5-8 FPD equipment (Samsung, LG….)
  - Newspaper style web printing (KM-GE?)
- Need for fine patterning is uncertain
  - 10 µm accuracy may be enough in registration and critical dimension
  - Light extraction layer may need submicron patterning over large area
- Reliability & Reproducibility
  - Avoid binning, returns and recalls

Manufacturing –Reliability & Reproducibility

- Quality Control Challenges at all Levels
  - Input materials
    - Purity of organics
    - Cleanliness & smoothness of substrates
    - Integrity of barrier layers
  - In-line monitoring
    - Process control
    - Defect detection
  - Rapid back-end inspection & test
- Reproducibility
  - Luminance: $\pm$10%?
  - Color coordinates: within 2-step Macadam ellipse



Source:Yoshi Ohno (NIST)

Bardsley Consulting

Commercial OLED Lighting Panels

Manufacturing Cost Breakdown: Moser Baer Estimate for 2012/13

2012/13 Target Unit Manufacturing Cost (per sq.m)	$ 250
Annual Product Shipments	5,500,000

Unit Manufacturing Cost Breakdown (MP) Module assembly materials not included	Mass Production ($/m2)		
Total	**$**	**250.00**	
Substrate	$	40.00	16%
OLED Materials	$	50.00	20%
Encapsulation Materials	$	20.00	8%
Indirect Materials	$	10.00	4%
Labor Cost	$	40.00	16%
Depreciation	$	50.00	20%
Overhead Expenses	$	25.00	10%
Business Expenses	$	15.00	6%
			100%

Assumptions

1) OLED Materials Utilization ~ 50%;
2) Substrate = Glass + LEL + TCO + Other Layers + Patterning;
3) Product Size = 150 x 150 mm
4) Module BOM & Assembly Costs not included

Source: Gopalan Rajeswaran

moserbaer

RT Projected Materials Costs* of OLED Lighting Panels(sheet processed) achieved through advancements

Stage	Units	Year		
		2011	2013	2015
Organic Materials (Material Utilization)	$\$/m^2$	50 (30%)	20 (50%)	10 (70%)
Substrate	$\$/m^2$	50	7	7
Electrodes	$\$/m^2$	30	30	15
Light extraction	$\$/m^2$	20	15	30
Encapsulation	$\$/m^2$	100	15	10
Other materials	$\$/m^2$	20	15	10
Total Cost	$\$/m^2$	340	122	86
	\$/klm	110	20	9

*Focus on added cost of materials rather than labor and capital

Source: Harry Buhay

Glass R&D

PPG

in

How Do We Get Cost Down?

OLEDWorks

Component	Requirement	Targets	Cost Contribution
Equipment (Entire Line)	Low cost High throughput	< \$100 capital/m^2/yr < \$30M total cost	< \$20/m^2
OLED Materials	High utilization Low cost	> 70% utilization > 50% cost reduction	< \$10/m^2
Other Materials	Low cost	Glass: < \$5/m^2 Light Extraction: < \$5/m^2 TCO: < \$5/m^2 Encapsulation: < \$10/m^2 Other: < \$5/m^2	< \$30/m^2
Labor	Highly automated for US manufacturing	< 30 operators/line for 24/7 operation	< \$5/m^2

- **Highest priority is low cost/high throughput equipment for every step of the manufacturing process (highest cost step is OLED stack deposition).**
- **Second highest priority is low cost "other materials" (OLED materials cost will decrease due to display volume growth).**

Source: Michael Boroson

Display vs Float Glass Comparison

Property	Borosilicate Glass	2-Side Polished Float Glass	Float Glass
Smoothness	Good	Good	Acceptable for OLED Lighting
Alkali Leeching	Good	Poor; May be acceptable with Na Barrier	Poor; May be acceptable with Na Barrier
Temperability	Poor	"Poor"	Good
Large Area	Yes	No	Yes
Cost ($/m^2)	~40	~10	~4-6

Main Driver (Cost)

DISPLAY INDUSTRY (Borosilicate Glass, 2-Side Polished Float Glass)

Glass R&D

PPG

Source: Harry Buhay

Manufacturing – Depreciation Costs

Assume

- Gen 4 line (730 x 920 mm)
- 2 minute cycle time; 24 hour, 7 day operation
- Annual capacity: 176,500 m^2 (substrate area)
- Facilities cost: $150M

Line Utilization Factor and Depreciation Costs:

	Start	Average	Target
Product Area (ratio)	0.7	0.8	0.9
Up time (ratio)	0.6	0.75	0.9
Yield (ratio)	0.6	0.75	0.9
Utilization factor	0.25	0.42	0.73
Depreciation - $ per m^2	675	405	230

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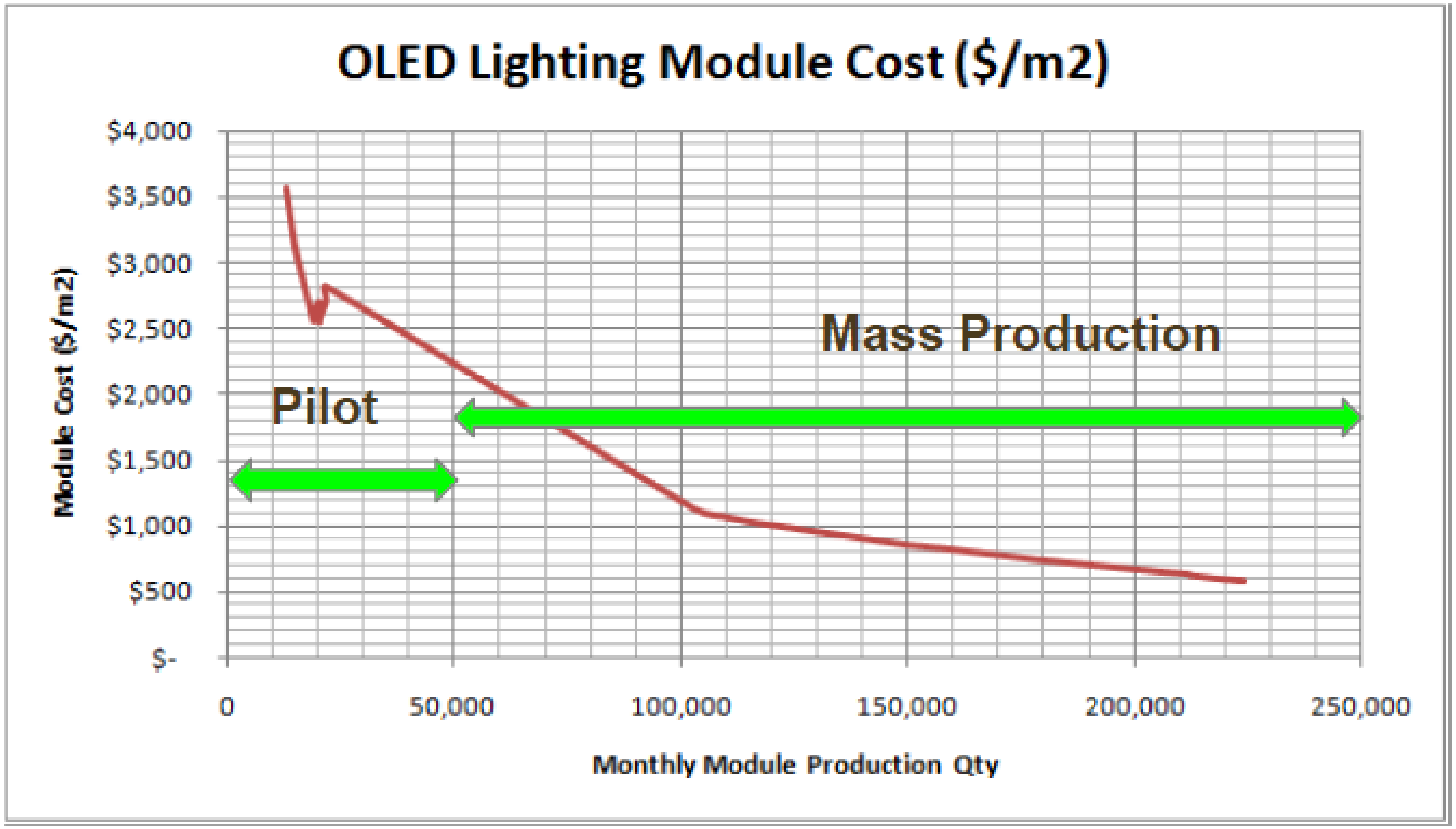
Manufacturing Cost Estimate (April 2011 update)

Moser Baer Update for 2013 (Production Capacity ~ 2.5Mn/Yr



Assumptions

1) OLED Materials Utilization: Pilot ~ 30%; Mass Production ~ 50%
2) Integrated Substrates: Light Extraction, TCO
3) Product Size = 150 x 150 mm
4) Module Bill-of-Materials included = 30% of total materials costs (assumption)

Source: Gopalan Rajeswaran

moserbaer

Meanwhile…

ILED developers are reducing their cost projections as they increase their performance targets

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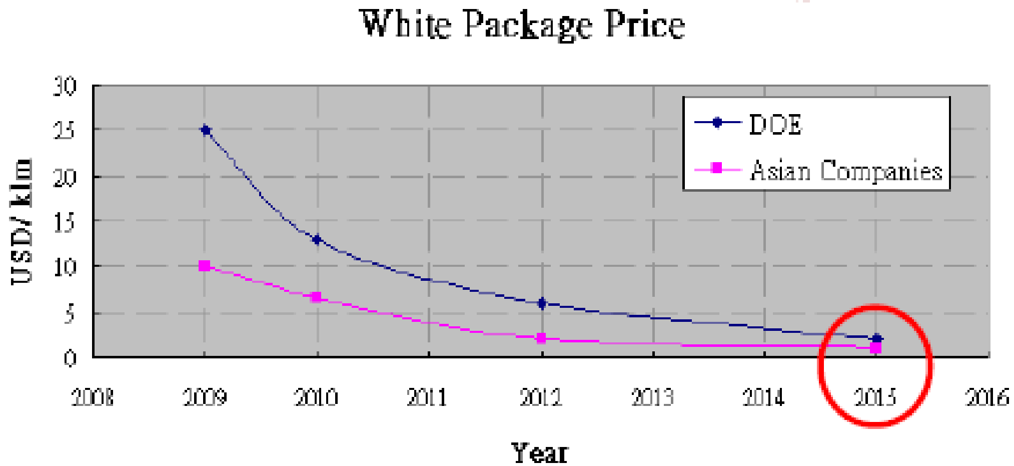
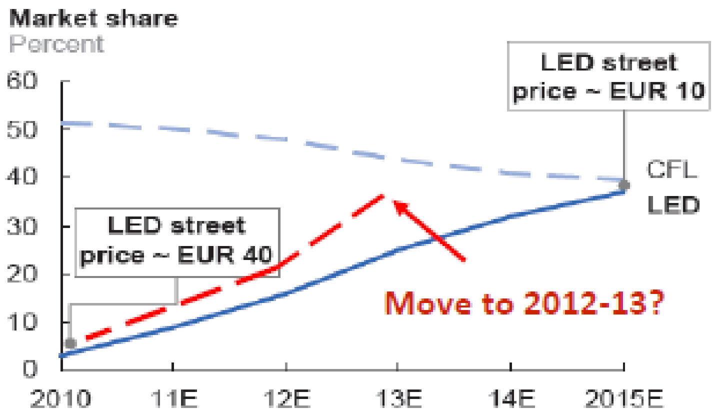
Can we reach 500 lm/$ Package @ 2012….2013

- Asian companies learn from LED TV offers good lm/$ LED packages
- Collaboration between performance leader and cost leader make it happen

USD / klm	2009	2010	2012	2015
DOE	25	13	6	2
Asian Companies	10	6.6	2	1



Current forecast sees CFL parity only as of 2015



Source : McKinsey 2010

1,000 lm/$ @ 2015

The Valley of Death

Improving yield and reducing manufacturing requires
practice, practice, practice....

What is right scale for a first production line?

How we do pay for the learning experience?

Bardsley Consulting

Outline

- What is the market opportunity?
  - Form, fit, function and flair
  - Energy savings
  - Light control
- Efficacy – key to long life & low cost
  - Light extraction
  - Voltage reduction
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