Introduction to OLED lighting and key challenges for the industry

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OLEDs

A new perception of light

- Rather than a beam emerging from a single light-emitting point, light coming from the larger surface provides pleasant, uniform illumination.
- The OLED produces a soft light, casting *no shadows, no glare and cool to the touch*: It is about pureness and subtle beauty.
- All actions of staging the light between instant on and smooth dimming are possible.
- New approach to handle lighting:
- Do not hide the light source anymore!

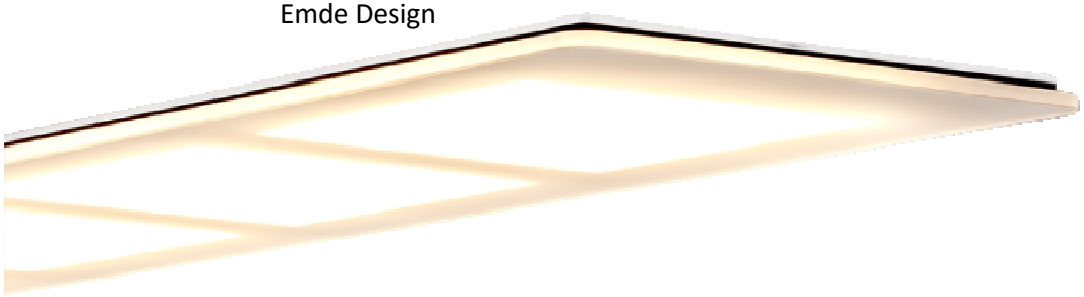
Vision

- In 10 years there will be only Solid State Lighting; shared between LED and OLED
- Applications favoring OLED:
  - Close to the user
    - Low glare, low temperature, broad spectrum – e.g. office above
  - Unique form factors of OLED:
    - Thin and light weight – for example transportation
    - Special design elements – for example curved lights

Outline

- Introduction to OLEDWorks
- Basics of OLED Lighting
- Product Examples
- Technical Challenges
  - Flexible OLED lighting
    - Offer new value proposition
  - Manufacturing @ low cost
    - Grow market for general lighting

Emde Design



Visa Lighting's Petal and Limit luminaires

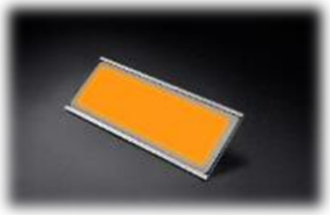
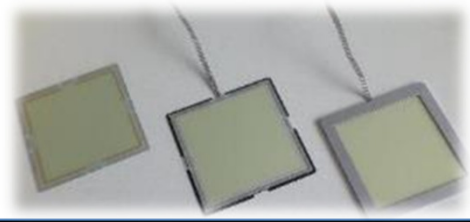
OLEDWorks – Our History

- **Founded 2010**
  - By OLED pioneers in Rochester, New York formerly of Eastman Kodak Company
  - Initial focus on R&D and Consulting
- **2011 – 2014: Class A equity raise complete based on unique OLED lighting business plan**
  - R&D lab completed and contract research underway
  - Novel Rochester production facility with emphasis on versatility, low cost expansion and low cost manufacturing is designed, built
  - OLEDWorks ships first prototypes from qualified manufacturing facility in Rochester
- **2015: Combination of two world-class teams, complete additional equity raise**
  - OLEDWorks acquires Philips OLED key assets
  - Includes worldwide state-of-the-art, largest capacity OLED lighting production line and rich OLED experience in Aachen, Germany
  - 70 worldwide OLED experts
- **2016: new products launched as OLEDWorks LLC and subsidiary OLEDWorks GmbH**
  - Lumiblade Brite 2 – 60lm/W, 3000K and 4000K, > 90 CRI, 300 lm/panel, >50,000 hour LT70 @ 3000cd/m2
  - Keuka OLED module
  - See www.oledworks.com for complete current product offerings

Over 400 years of OLED expertise supporting your OLED experience

OLEDWorks – What we do

- ***WE MAKE OLED LIGHT ENGINES***
- **OLED material, formulation, process and reliability experts**
- **OLED lighting manufacturing innovation**
  - Aachen: Bold move to make world's brightest panels, high volume capacity
  - Rochester: Disruptive low cost structure, amber, low volume, scalable
  - Process integration competence
- **OLED collaboration and integration**
  - Driver and electronics support, technical support, supplier collaboration

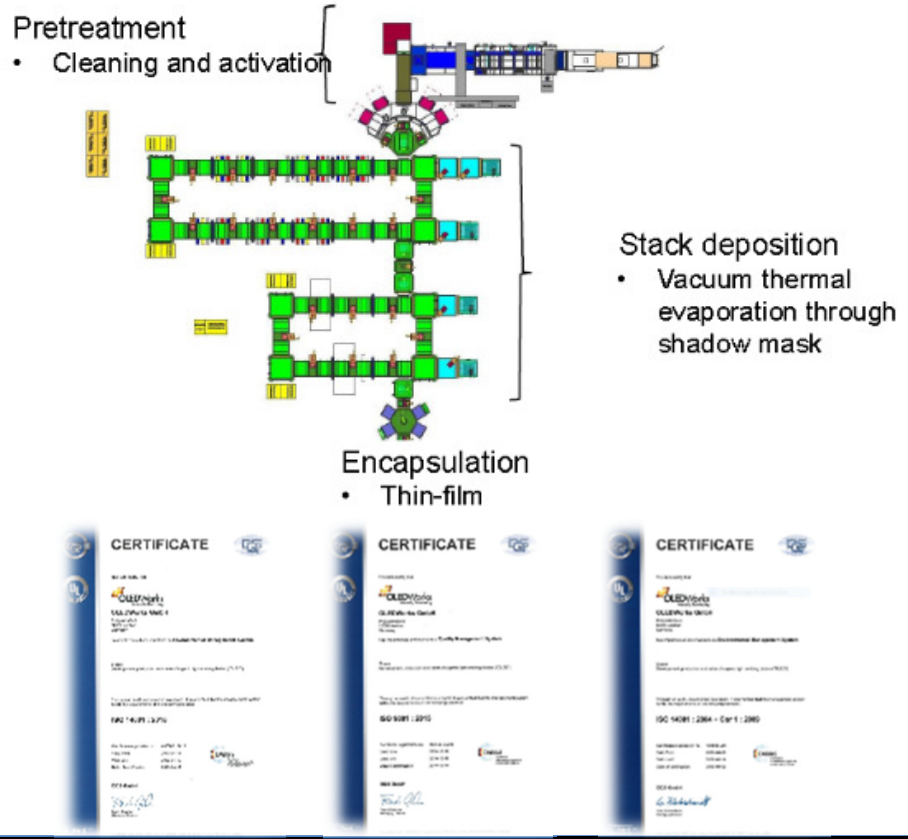




OLEDWorks capabilities

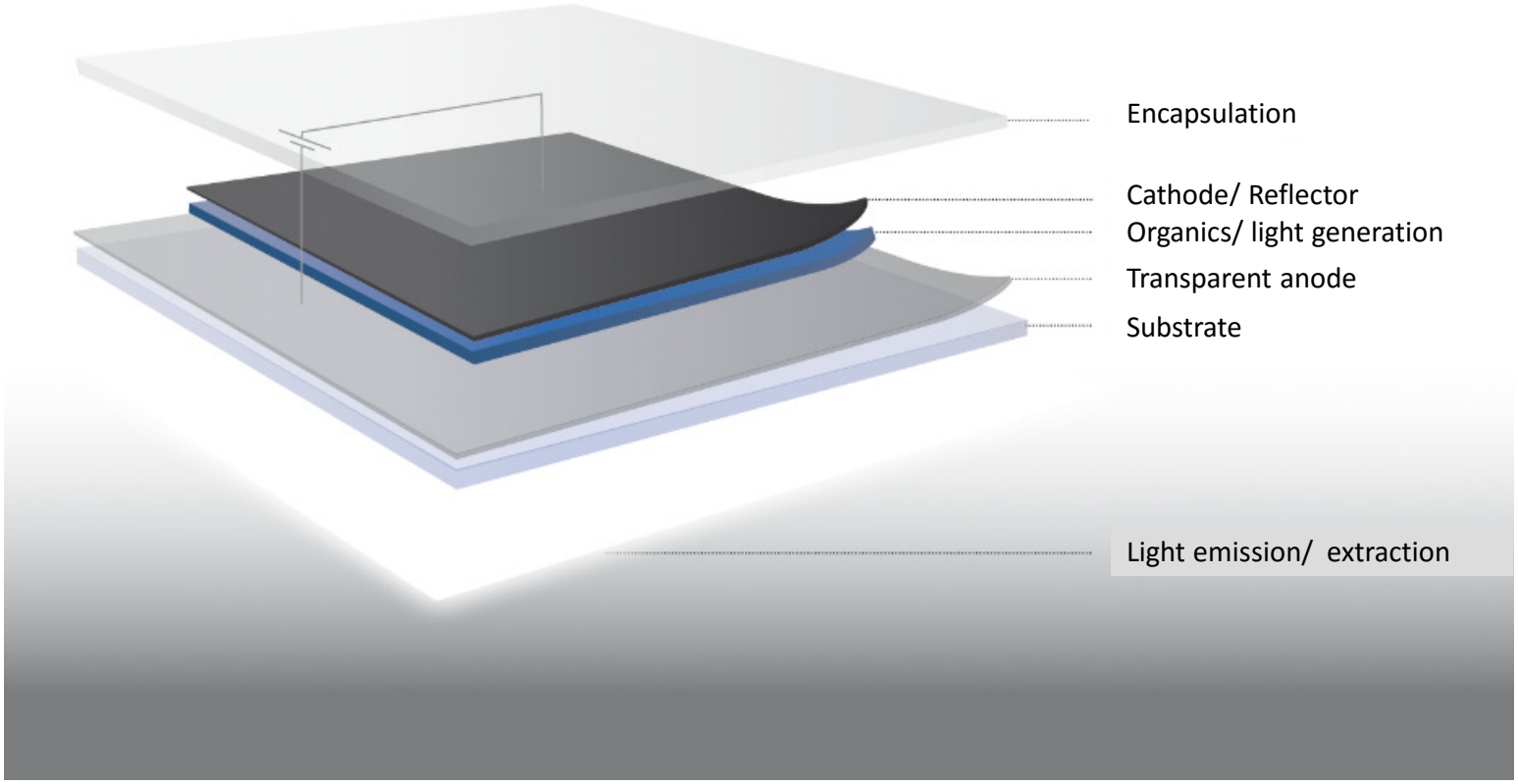
- Commercialized product offerings, all high brightness capable
  - High brightness white – square and rectangular (Brite 1: FL300 + FL300L)
- Research and Development
  - Qualified DOE OLED testing facility
  - Tons of collaboration ongoing, a key to success in the U.S. and Europe
- Joint Development
  - Corning – Willow® Glass for application in bendable OLEDs
  - Philips® - Luminaires integrating bendable OLEDs

OLEDWorks Manufacturing Capacity

- In Aachen with worldwide biggest installed capacity for OLED Lighting
  - Current Throughput Capacity – 20,000 m2/year product post yield
  - Expansion Capacity – 120,000 m2/year product post yield
  - Incl. thin film encapsulation technology
- Rochester Manufacturing Line with scalable capacity
  - Production Capability – 3,000 m2/year scalable to 7,000 m2/year
  - Demonstration of Unique Large-Scale Production Technology
- ISO 9001:2015, ISO 14001:2015, BS OHSAS 18001:2007 certified facility

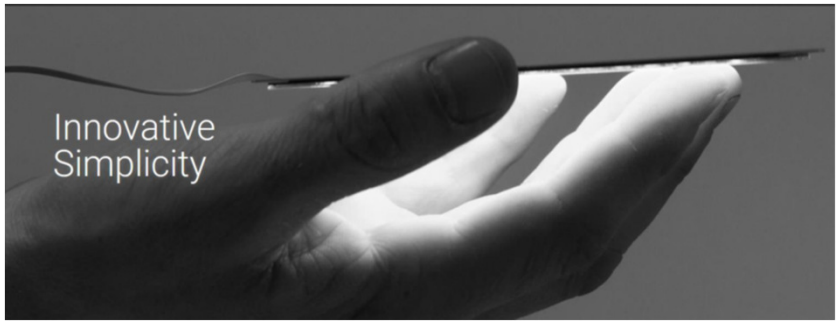


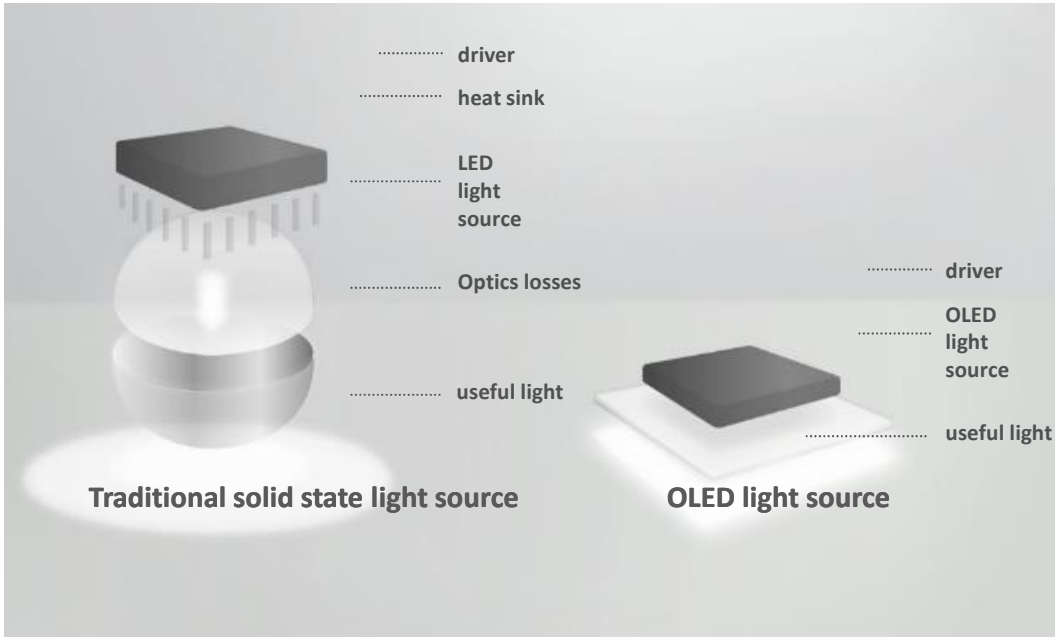
The OLED principle



OLEDWorks enables you to revel in possibility

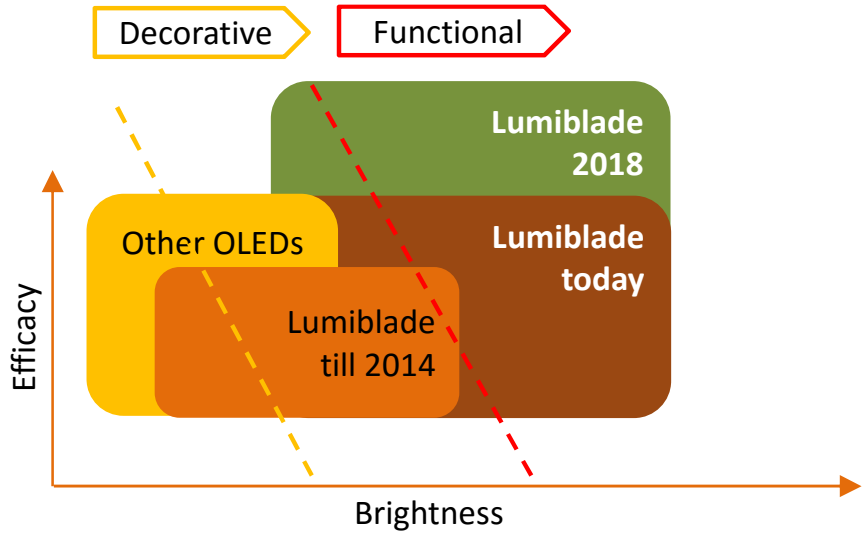
- Design Freely
- Create Passionately
- Be Unlimited with Light



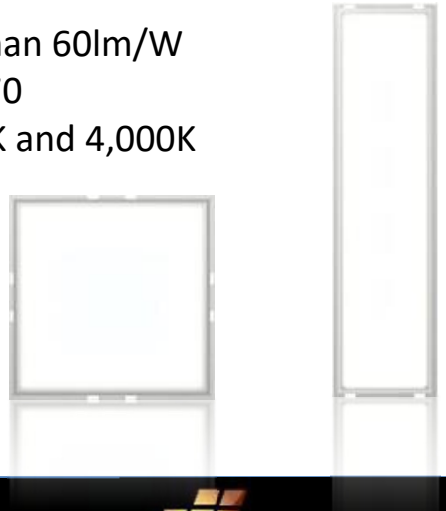


OLEDWorks enables you to revel in possibility

- **2nd generation (Brite2) was launched 2016, 3rd generation follows in 2018**
- OLEDWorks Lumiblade standout performance with the Brite family
- Higher brightness enables many additional applications and is „only OLEDWorks“

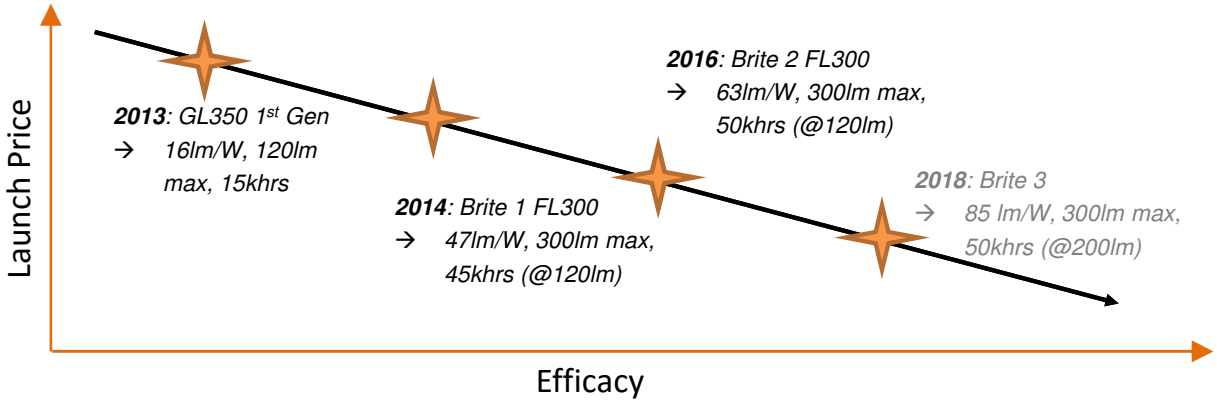


Brite 2
Efficacy of more than 60lm/W
CRI > 90 and R9 >70
Available in 3,000K and 4,000K



Commercial product performance on steep curve

- **For commercial products in the last 3 years we…**
- **…tripled the efficacy**
  …tripled the luminance
  …tripled the lifetime,
- **…and cut the price by 3**
- **…and it does not stop here !**



OLED Panel Performance Today

From 2016 DOE SSL R&D Plan

Today's panel performance:

- >20klm/m^2
- Efficacy of >60 lm/W
- LT70 >50k hours
- CRI > 90
- R9 > 50
- These panels deliver the performance needed for most applications

OLEDWorks Brite 3 with >90 lm/W – for release in early 2018

New!

Table 6.1 Components of OLED Panel Efficacy

Source	LG	LG	OLEDWorks	OLEDWorks
Product	LL055RS1-62P1[1]	LL055RS1-92P1[1]	Brite 1[2]	Brite 2
Illuminance (lm/m^2)	7,700	7,700	20,700	20,700
LER (lm/W)	328	328	336	302
Electrical Efficiency (%)	80	80	73	70
Internal Quantum Efficiency (%)	65	65	62	62
Extraction Efficiency	35%	52%	31%	47%
Panel Efficiency (%)	18	27	14	21
Panel Efficacy (lm/W)	60	90	46	62
CCT (K)	2700	2700	2900	2956
CRI (R_a)	>87	>87	80	93
CRI (R_9)				76
Lifetime (L_{70}) (hrs)	40,000	40,000	>50,000	>50,000

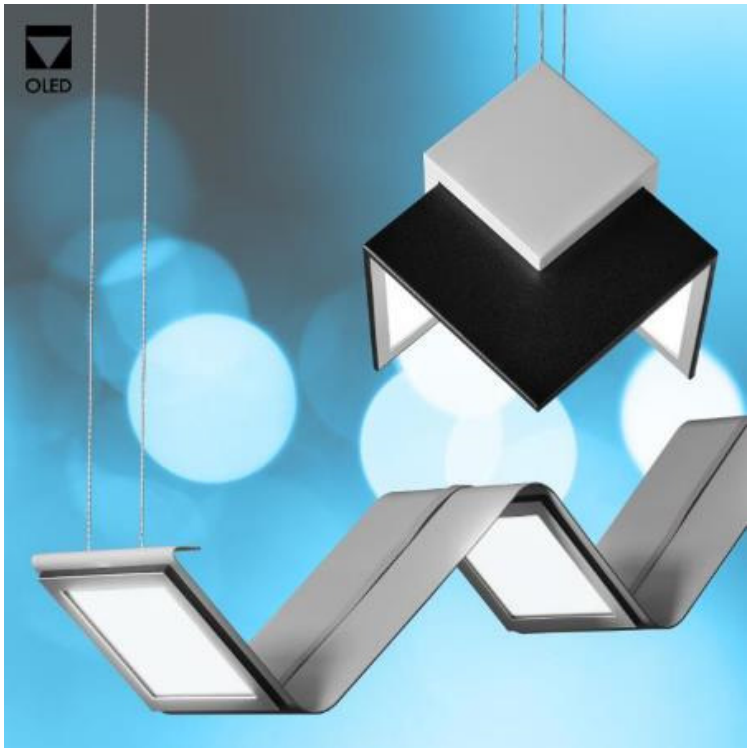
Note: All data provided in communications with represented company.

1. A hybrid triple stack with fluorescent blue emitters and phosphorescent red and green; 2700K
2. A hybrid 6-stage stack with fluorescent blue emitters and phosphorescent red and green; 2700K A double stack with all phosphorescent emitters **[111]**

DOE SSL R&D Plan, June 2016, pg 102
Illuminances corrected for total panel area
Efficacy and Lifetime (L70) is quoted for 3000 cd/m2

LED vs OLED Cost Comparison

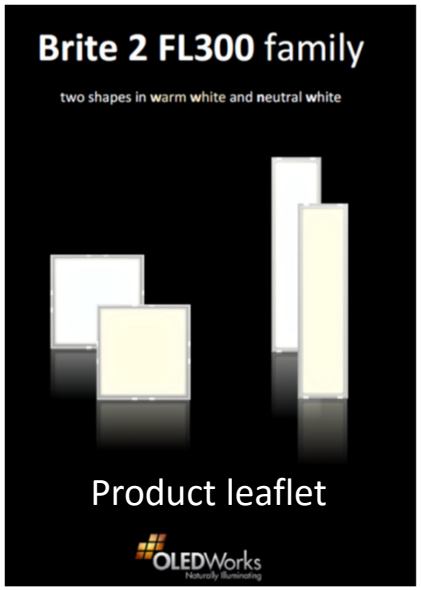
- OLED light panels can be at higher prices ($/klm) and still have fixture cost-parity, due to simpler fixture designs for lower costs.
  - No optics, no heat management, simpler mechanical designs.
  - Higher brightness OLED panels are important
- LED fixtures cover wide quality range
  - OLED can compete now at the high end.
- Unique form factor of OLEDs can give a design advantage that is difficult for LED to match.

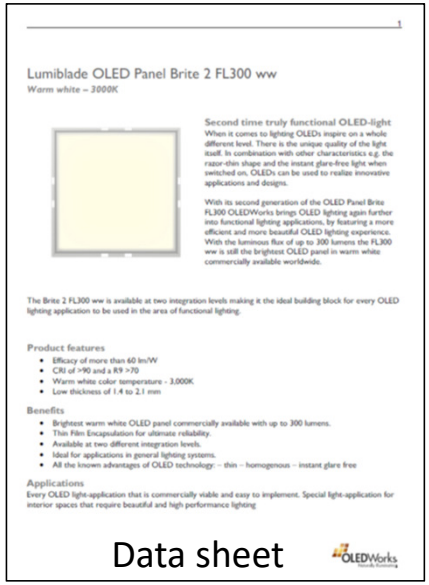


Visa Lighting's Petal and Limit luminaires

For more information

- Please visit our homepage to download detailed product information:
- www.oledworks.com/products/brite-2/
- Contact us: owinfo@oledworks.com





“The Source” in Aquis Plaza

Carl Stahl Architektur

OLED light sculpture in Frankfurt

Hatec with Groß + Partner & Eicke Becker

OLED luminaires at “Theater an der Elbe”

500xFL300 as the center piece of the new musical theater

OLED luminaires at the Audi Forum

Worldwide first use of OLEDs for functional lighting

DKB Offices – DOE Gateway

LIMIT™ & PETAL™

Visa Lighting

Emde Design

Aerelight A1

Aerelight Design

Philips ThinAir OLED luminaire

The modular OLED luminaire for office and retail

Motivation for Curved and Bendable OLED Lighting

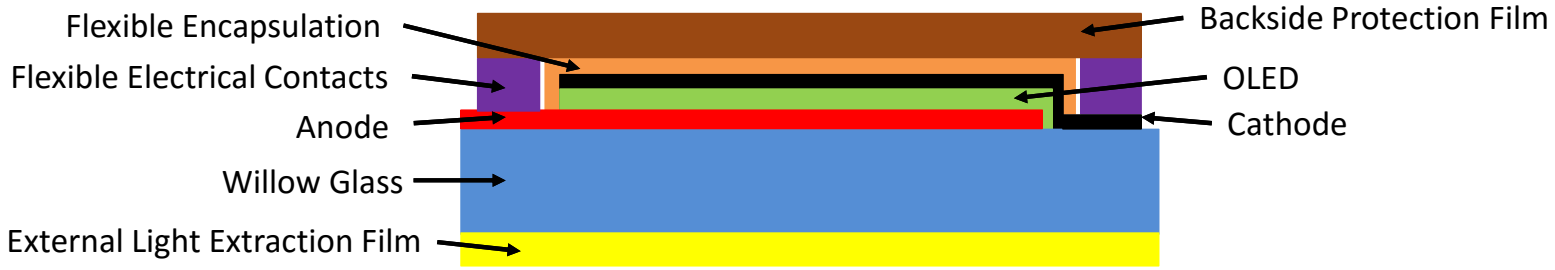
- OLED lighting is currently higher priced than LED, and needs to achieve higher sales volumes to significantly reduce costs.
- Unique selling points – OLED lighting can be bendable, flexible, thinner, lighter than LED – allowing more creative designs.
- Roll-to-Roll – the final challenge – can result in further cost-down in mass manufacturing.

Selection of Substrate: Glass vs Barrier-Coated Plastic

- Glass Advantages
  - Excellent barrier properties
  - Lower cost than barrier-coated plastic
  - Available now in wide rolls
  - High transparency
  - High temperature processing capability
- Glass Disadvantages
  - Defects on surfaces and edges limit maximum stress and radius of curvature
  - Bending/twisting in 2D results in breakage
    - In processing - e.g. in deposition/encapsulation equipment.
    - In handling of finished product.
- OLEDWorks and Corning have a Joint Development project for OLED lighting on Willow glass.

Design Challenges of Flexible Glass OLED Structures

Typical Structure

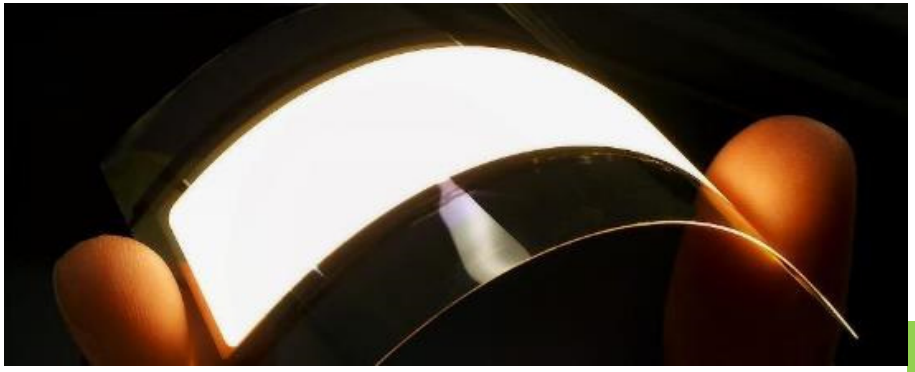


- Careful engineering and design required to make the OLED product robust to handling
  - Selection of materials and thicknesses is critical to control stress and strain in each layer
    - The design of the location of neutral axis during bending is important
- Protection of glass surfaces and glass edges is required to prevent damage which weaken the glass
- Lamination onto surfaces with topography (multiple heights) adds stresses to the stack
  - Stresses during the lamination processes can result in breakage.

Bendable OLED Lighting Panel Product Properties

Lifetime
Reliability
Efficacy
Uniformity

Curvature of OLED Panel without Breaking Glass or Encapsulation

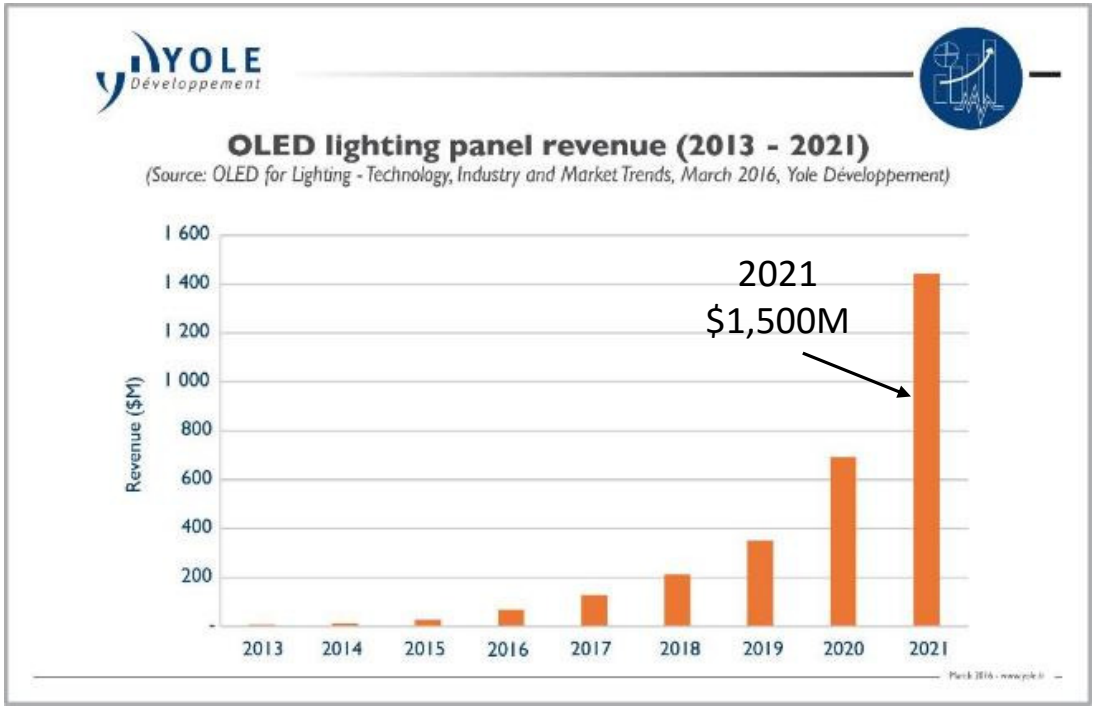


Thickness
Weight
Bendable vs Flexible

Mechanical and Electrical Connection and Support

Market request is to match rigid technology platforms in price performance while additionally offer USP‘s bendable OLED‘s

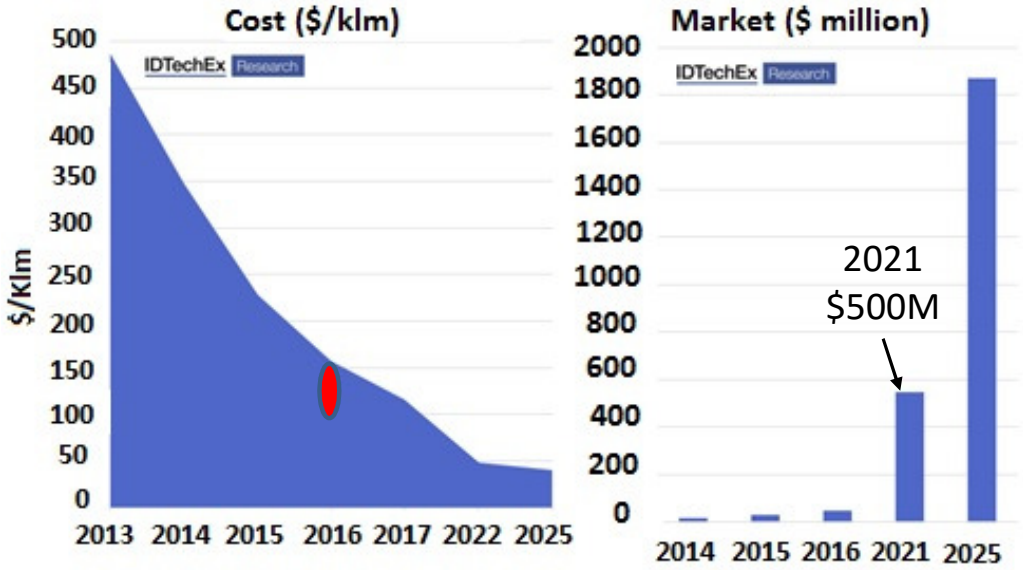
OLED Panel Revenue Growth Prediction by Yole in March 2016



OLED lighting market as described by panel sales could grow by >10x in the next 5 years.

This is a average CAGR of > 50%/year.

Prediction of Panel Prices and Volumes



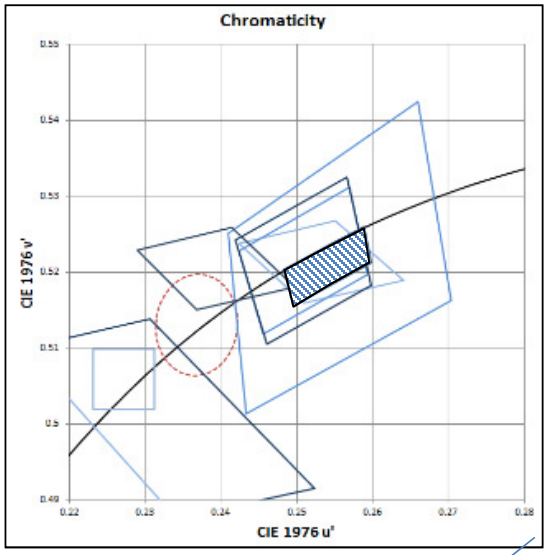
OLED panel prices and market - IDTechEx predictions in 2013, unchanged in 2016

Panel prices – the industry is ahead of the curve as shown by red ellipse.

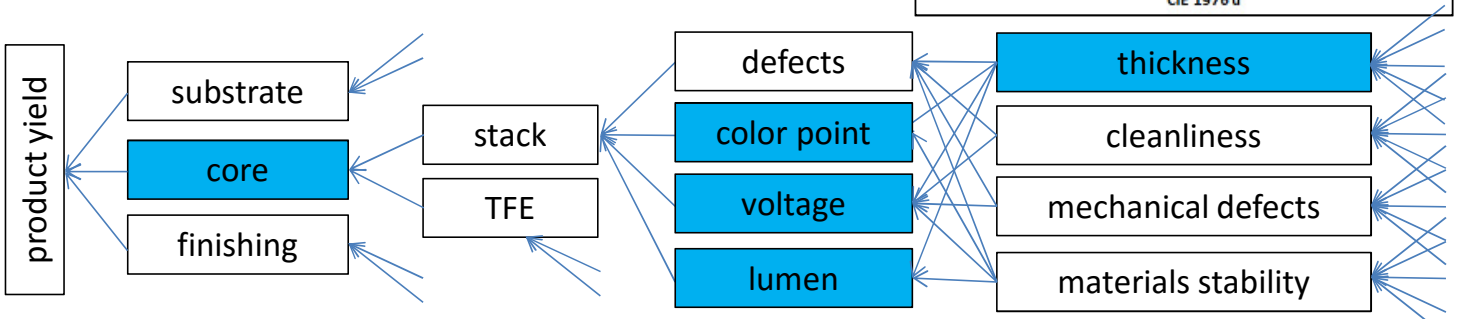
From "OLED Lighting Opportunities 2016-2026: Forecasts, Technologies, Players", April 2016
http://www.idtechex.com/research/reports/oled-lighting-opportunities-2016-2026-forecasts-technologies-players-000472.asp

Manufacturing yield (capacity & cost)

- Meaningful targets
  - Inside color point box without binning (dashed)
  - No ‘esthetic defects’ (bright spots, dark spots, …)
  - Lumen output within 10% of nominal value
  - Voltage within 5% of nominal value
  - Lifetime, reliability within product specification

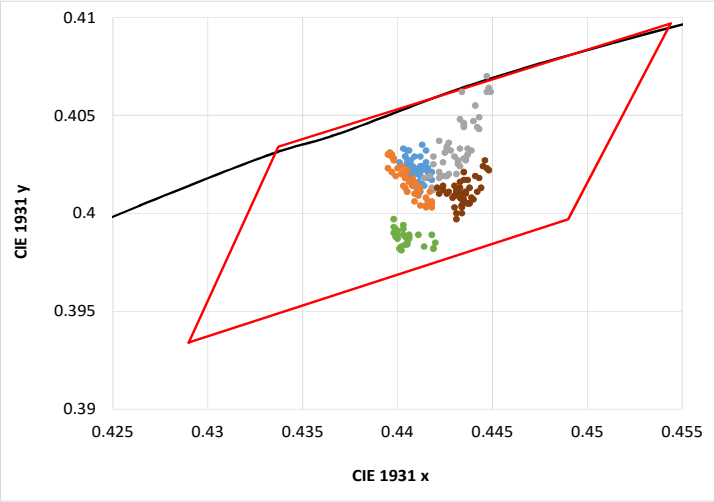


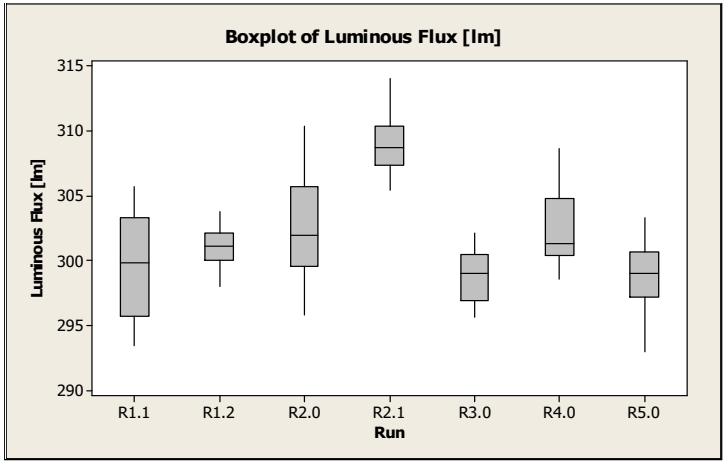
Yield break-down (incomplete)

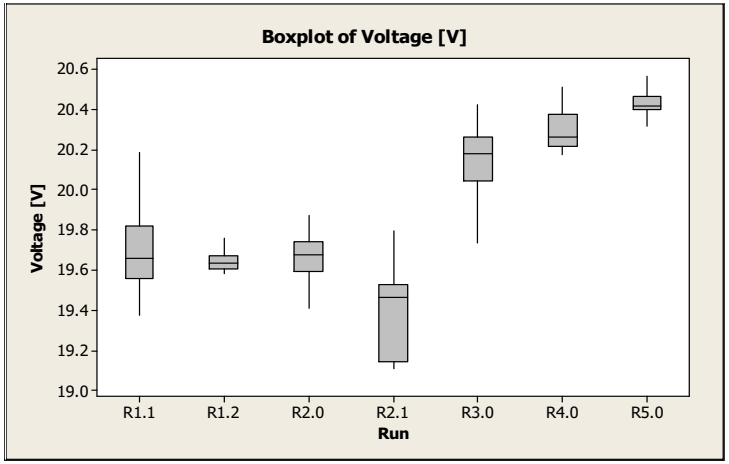


Run to run stack stability

- Repeatable on-plate and plate-to-plate stability
- Independent several-day continuous runs separated by down periods

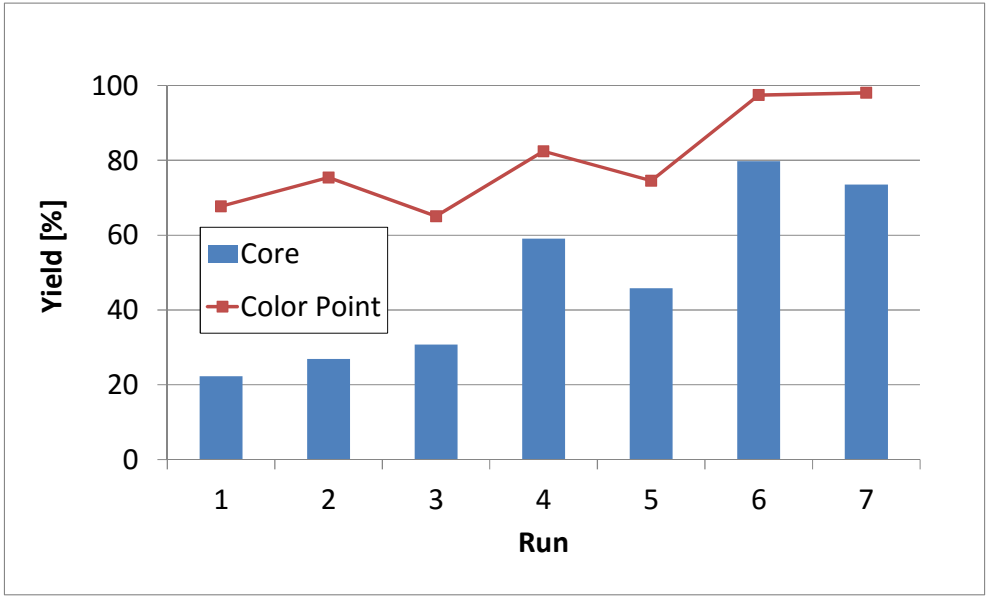






Yield

- Successful ramp-up to good yield
- Further yield improvements by solving several identified and understood issues
- Runs represent 6-month period
- ‘Color point’ comprises color point, voltage and lumen output
- ‘Core’ comprises stack and TFE



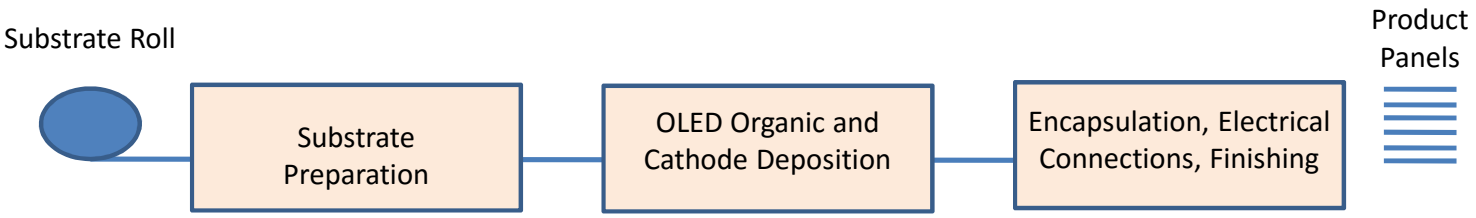
OLED Processing Costs

→ R2R Needed for Ultimate Low-Cost Production

- As volumes increase, OLED lighting industry will have cost reduction due to economies of scale over today's manufacturing machines
- Major cost-down advantages will occur when we get to G5 Sheet-to-sheet machines
  - LG machine will be in production in Asia in 2017-18
  - North America or Europe in 201x?
- For further cost down – mass production using R2R processing required
  - This make more sense then going to G8 – diverging from the display model.
  - Now is the time to start working on the developing and commercializing the technologies that will be required to make this happen.

Two Critical Areas Require Development for Successful R2R OLED Lighting Manufacturing

1. Substrate Web Handling and Transport
   - Substrate must roll up without particles and damage
   - Within the machine, all moving contact points generates particles
     - Worst problems are in areas where deposition occurs
2. Masking for Vacuum Thermal Evaporation Deposition is used to:
   - Prevent OLED organic from depositing the seal area and cathode contact area
   - Prevent the cathode from depositing across to the anode contact area.



Summary

- Solid State Lighting is the future and OLED will be a significant part of it.
- Applications where OLED will initially grow will be:
  - Close to the user – due to the high light quality, low glare, and low temperature.
  - Low volume and weight.
  - Products where design elements affect buying decisions
- The combination of thinness, lightness, and flexibility of OLED will be key differentiators from LED.
- OLEDWorks will continue to introduce products with higher performance, lower cost and unique form factors to grow the market.
- The commercialization of our first bendable products has started now!
- Key technologies are needed for low-cost R2R.
  - We need to work together to develop these now.