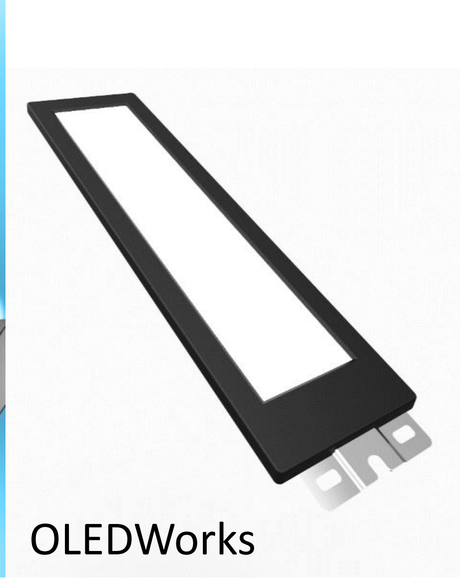
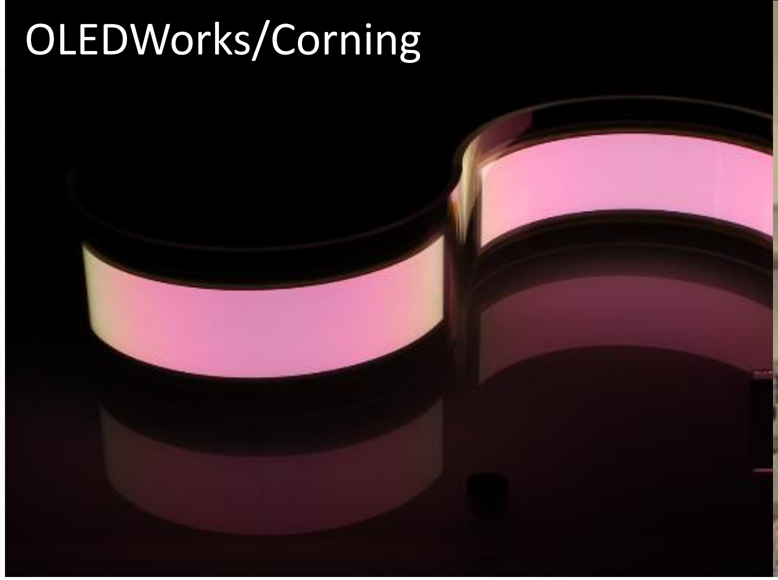
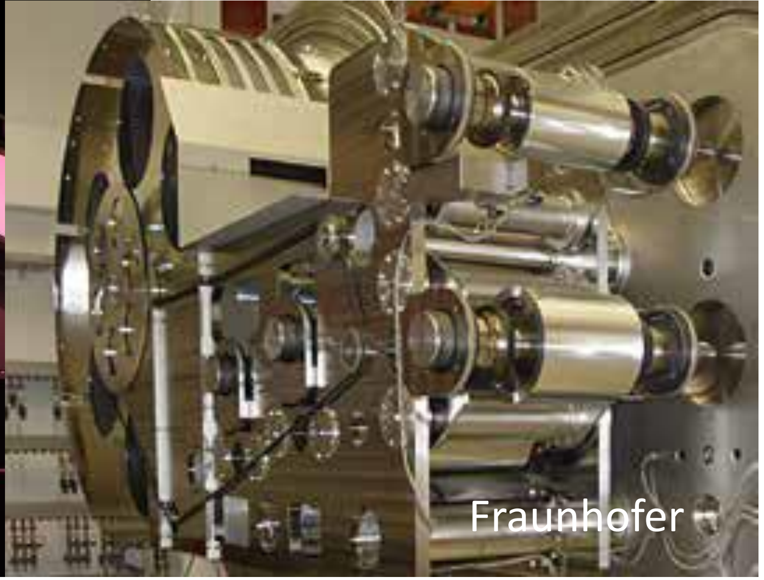






Progress and Manufacturing Challenges in OLED Lighting

John Hamer COO

OLEDWorks LLC

Outline

- Progress
  - Our Vision
  - Our Company
  - Performance and Pricing Trends
- Manufacturing Challenges
  - Cost vs. Volume
  - Grow Demand
  - Lower Cost
- Summary

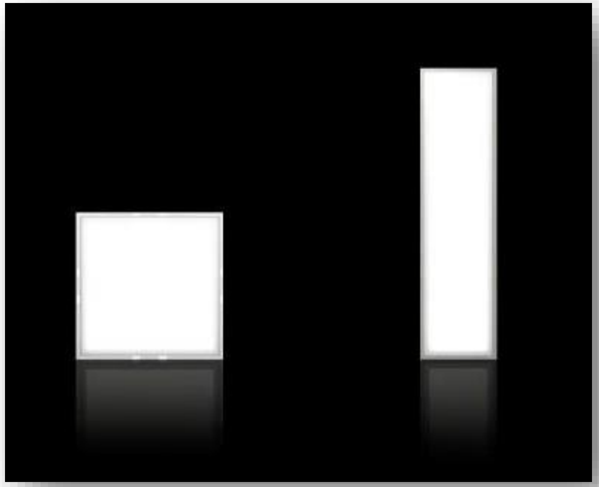
Our Vision

- Jump ahead 10 years, and we believe that we will find only Solid State Lighting being installed; shared between LED and OLED

- The lighting applications where OLED will be the favored will be:
  1. Applications that are close to the user
     - Low glare, low temperature, broad spectrum – e.g. office above
  2. Applications using the unique form factor of OLEDs:
     - Thin and light weight – for example transportation
     - With special design elements – for example curved lights – our buying decisions are strongly affected by design

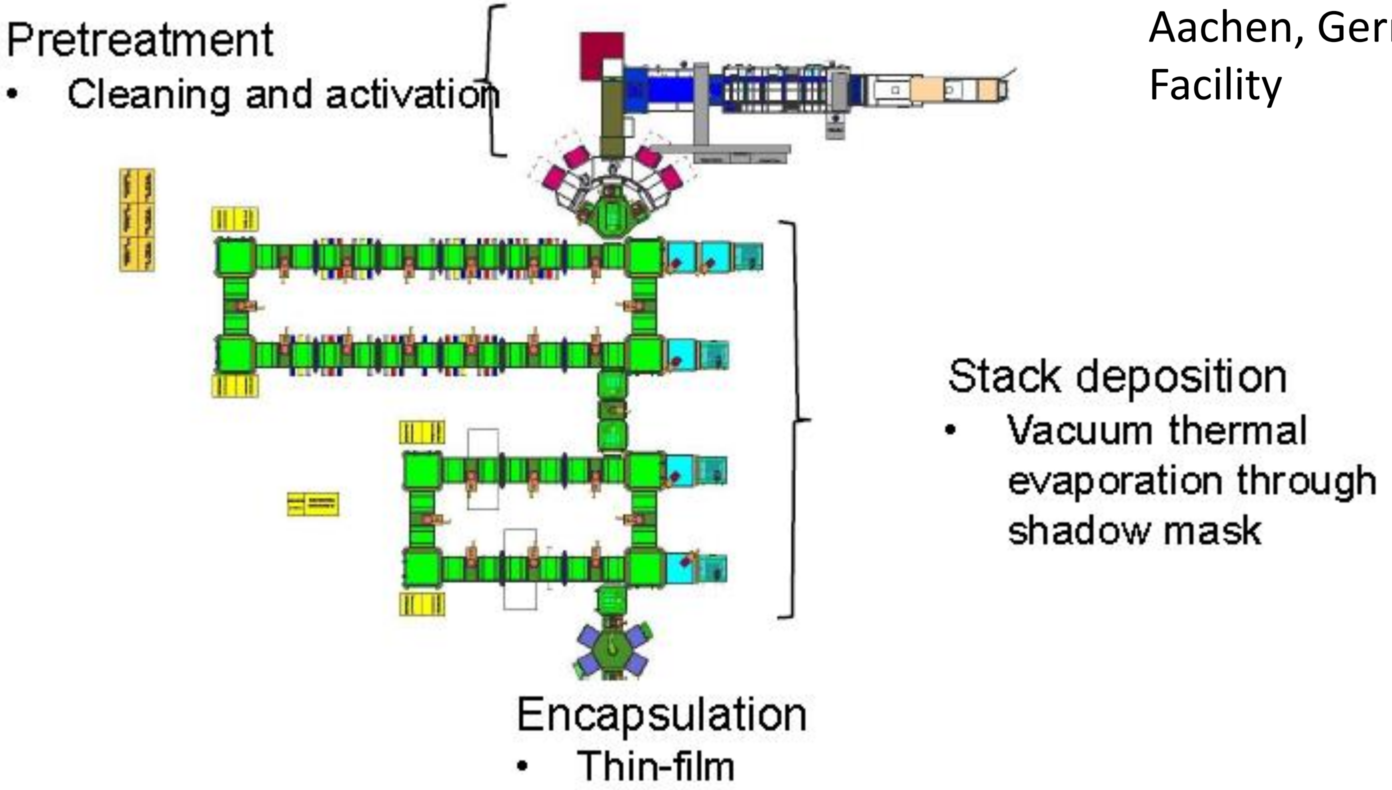
OLEDWorks – Our History

- **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

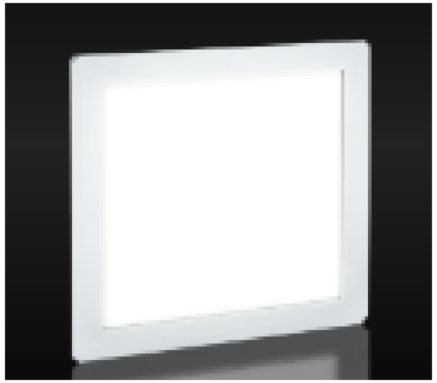


OLEDWorks Capabilities
State-of-the-Art OLED Manufacturing Facilities

Aachen, Germany
Facility



Competitive positioning



	OLEDWorks
Efficacy (lm/W)	>60
L70 (khr)	50 @ 3000 nit
CRI	>90
R9	>50
Application	Functional lighting
Grade of Industrialization	Very high – ISO 9001, 14001, 8001
Capacity (m^2)	20.000 – 120.000

- OLEDWorks well positioned with high grade of industrialization and forward plans
- Are OLED lighting panels positioned for market adoption?
  - ✓ Yes, surpass threshold for many applications

Performance: Panel Roadmap

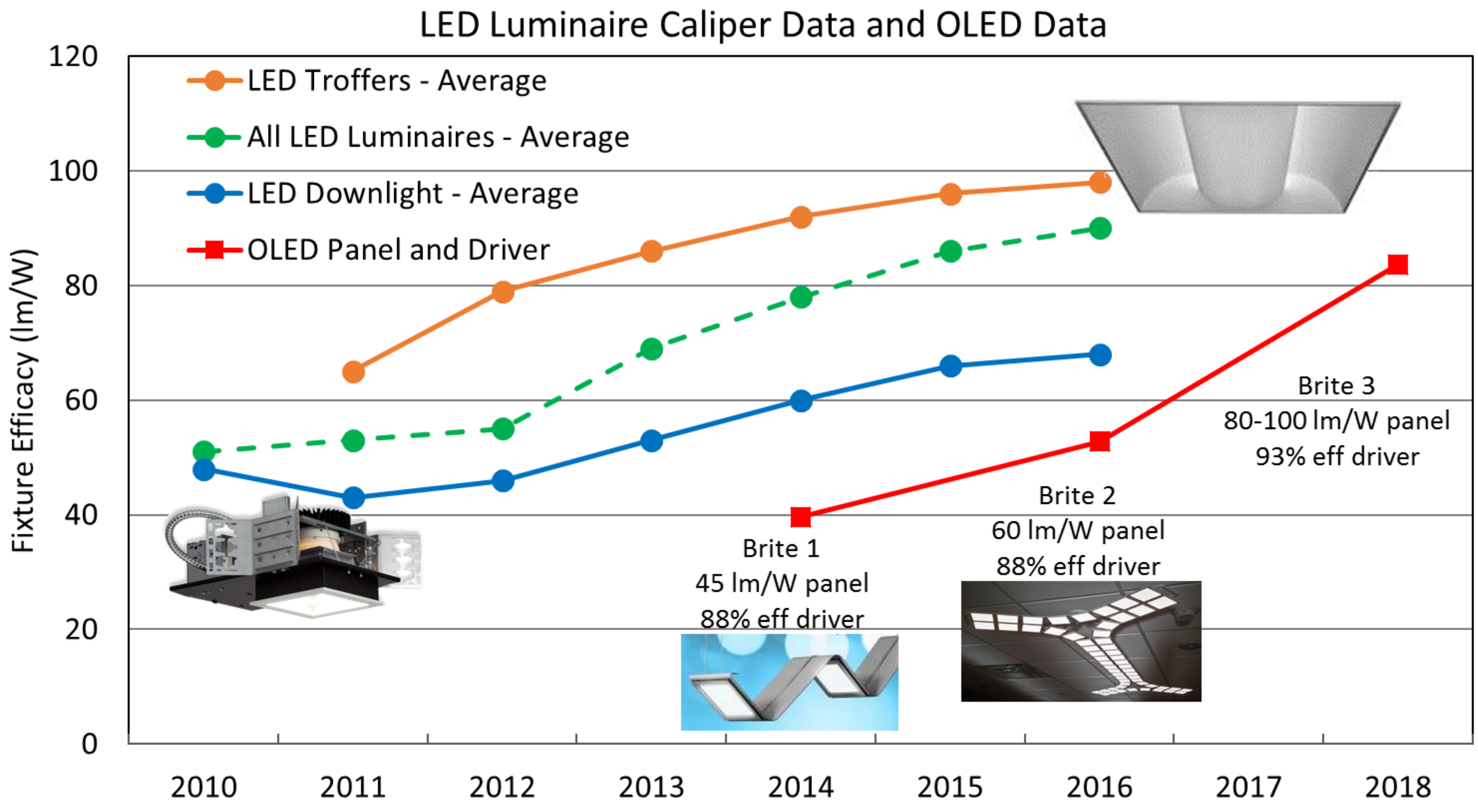
Brite FL family development
Brightness constant with 3 lm/cm²
High CRI (>90) and R9 (>70)

OLEDWorks Brite 3 with 80-100 lm/W – for release in early 2018

	2014/ 2015	2016	2018	2020
Efficacy	40 - 50 lm/W	50 - 70 lm/W	80 - 100 lm/W	>100 lm/W
Panel	rigid, 1 shape	rigid, 2 shapes	bendable + rigid, 4 shapes	bendable + rigid, >6 shapes
Lifetime L70	10 - 50khrs	10 - 50khrs	30 - 50khrs	>50khrs

€/cm²

Performance: Luminaire Efficacy Progress



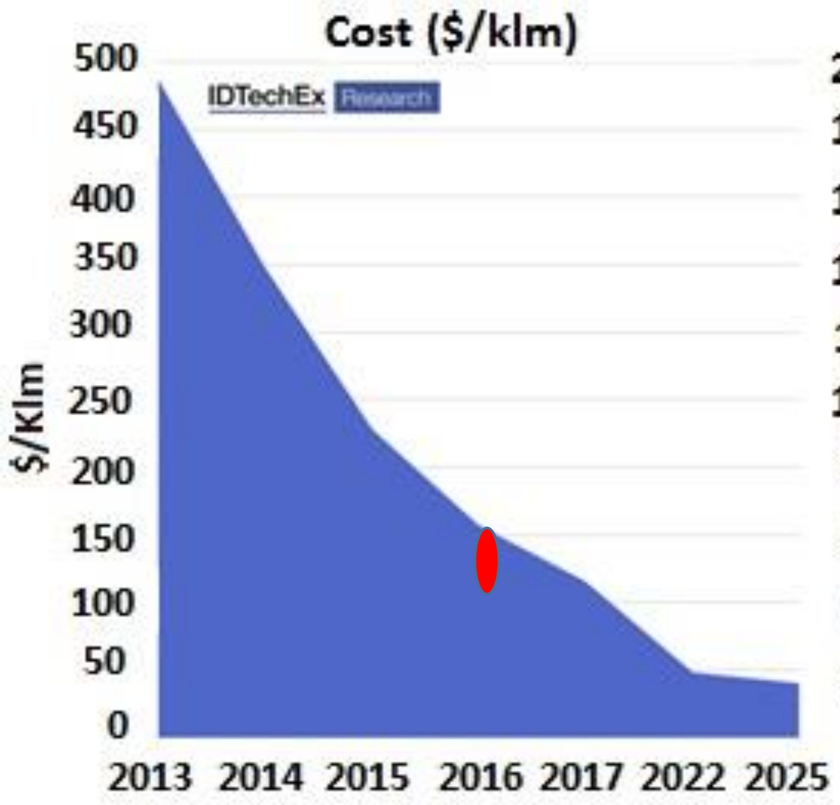
LED data from the DOE EERE CALiPER Snapshot report in April 2016.

These LED data represent the averages in the Lighting Facts Database and contain data on fixtures available in the market.

The OLED line shows OLEDWorks sequence of product offerings.

OLED-LED fixture efficacy gap is shrinking

Performance: Panel Prices and Volumes

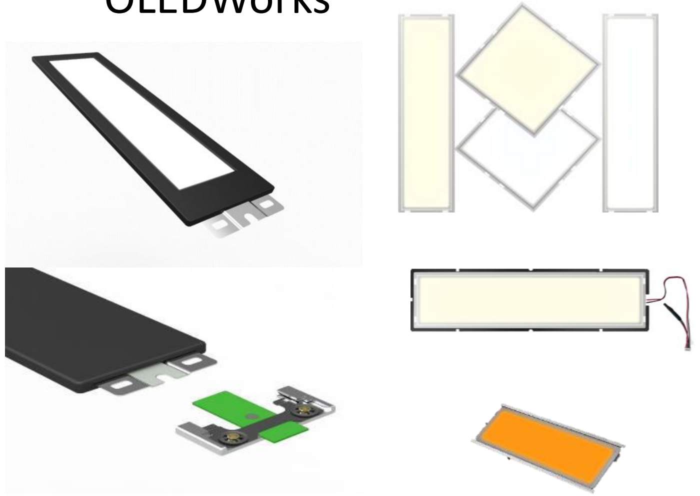


OLED panel prices and market - IDTechEx predictions in 2013, unchanged in 2016

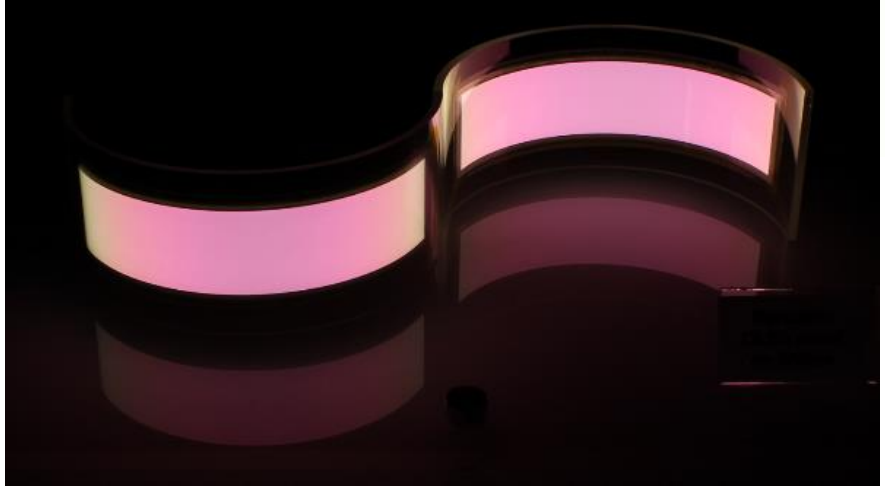
Panel prices – the industry is ahead of the curve as shown by red ellipse.

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

OLEDWorks

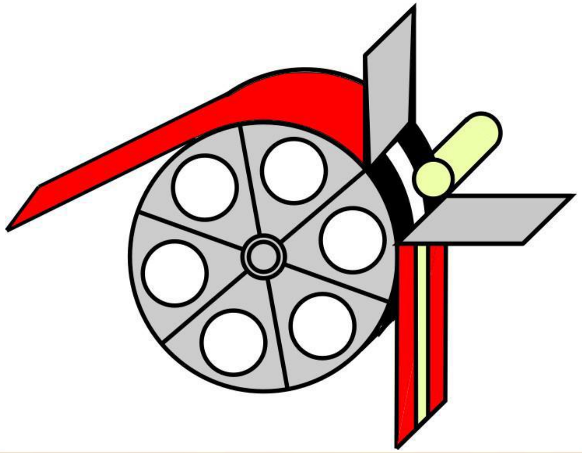


OLEDWorks/Corning

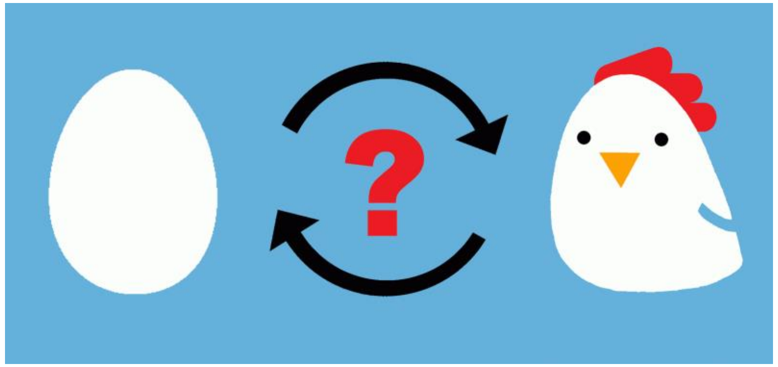


Konica Minolta

Manufacturing Challenges



Cost vs. Volume: Problem

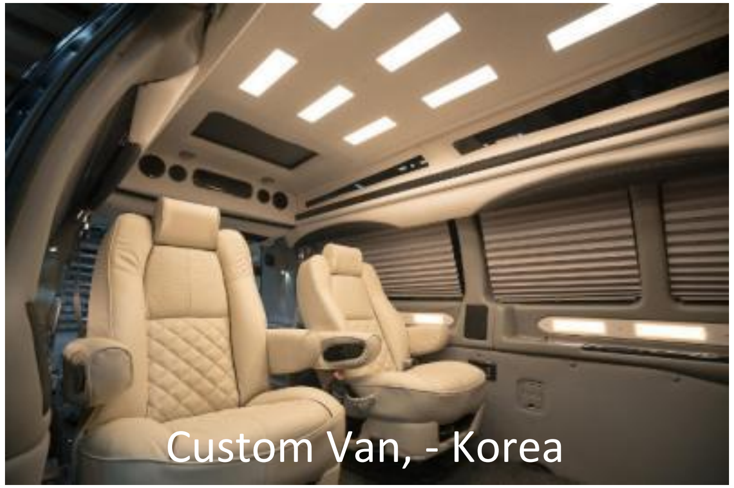


- We need to build a high capacity machine to be cost-attractive for general lighting for high volume
- However, we need to build sales volume to enable investment in a high capacity machine in US
  - For example – the initial capacity of LG G5 machine is about 10M panels/year post yield
    - (1.0mx1.2m, 15k sheets/mo, 80% yield, 60 panels/m2)
  - This is more than 100x current demand

➢We need to grow demand

Grow Demand:
Customers who want something special

- Restaurants, hotels, retail stores, offices, …
    - Look special or offer a special experience.
- Partner to design and build OLED fixtures to meet their needs.
- Build awareness and generate interest in short term.
- Other luminaire makers will follow when the leaders establish the path and vision.



Grow Demand: DKB Offices – DOE Gateway

US Department of Energy Gateway / NYSERDA Demonstration OLED project for 14,000 sq. ft. office space in Rochester completed in Sept 2016

This has resulted in sales of OLED luminaries to banks for use in their offices

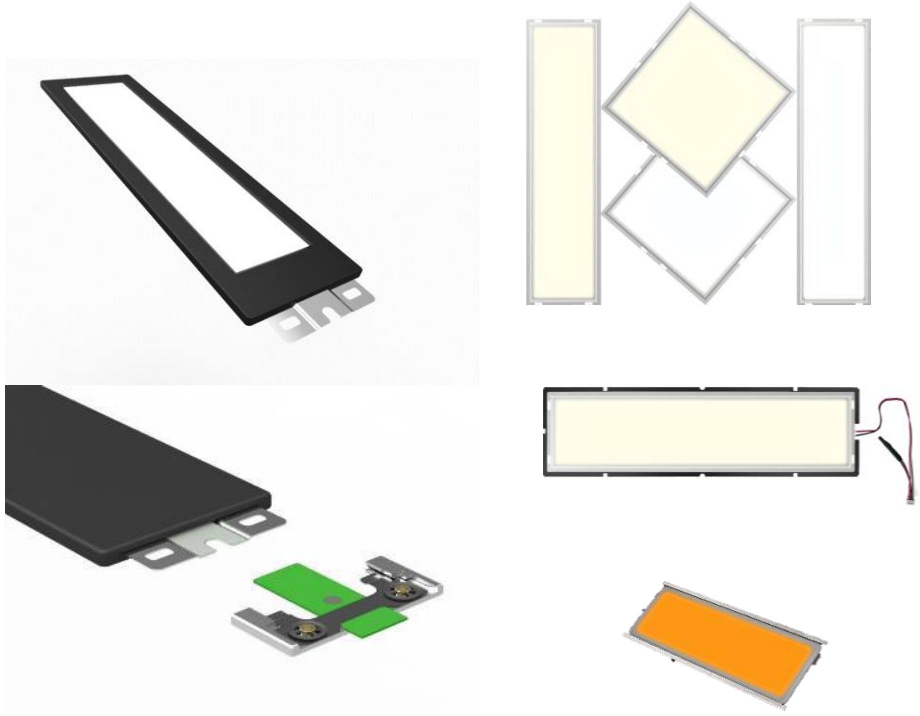
Grow Demand: Panel Variety and Integration Level

Panels: Size, Shape, Color Temperature & Color

Integration Level: Panels, Drivers, Connectors, Light Engines

LG Display

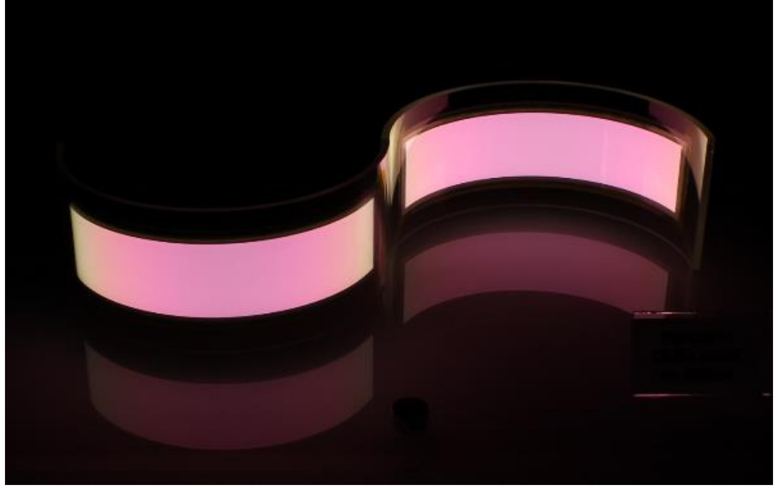
OLEDWorks



Grow Demand: Bendable, Flexible, Thinner, and Lighter Weight

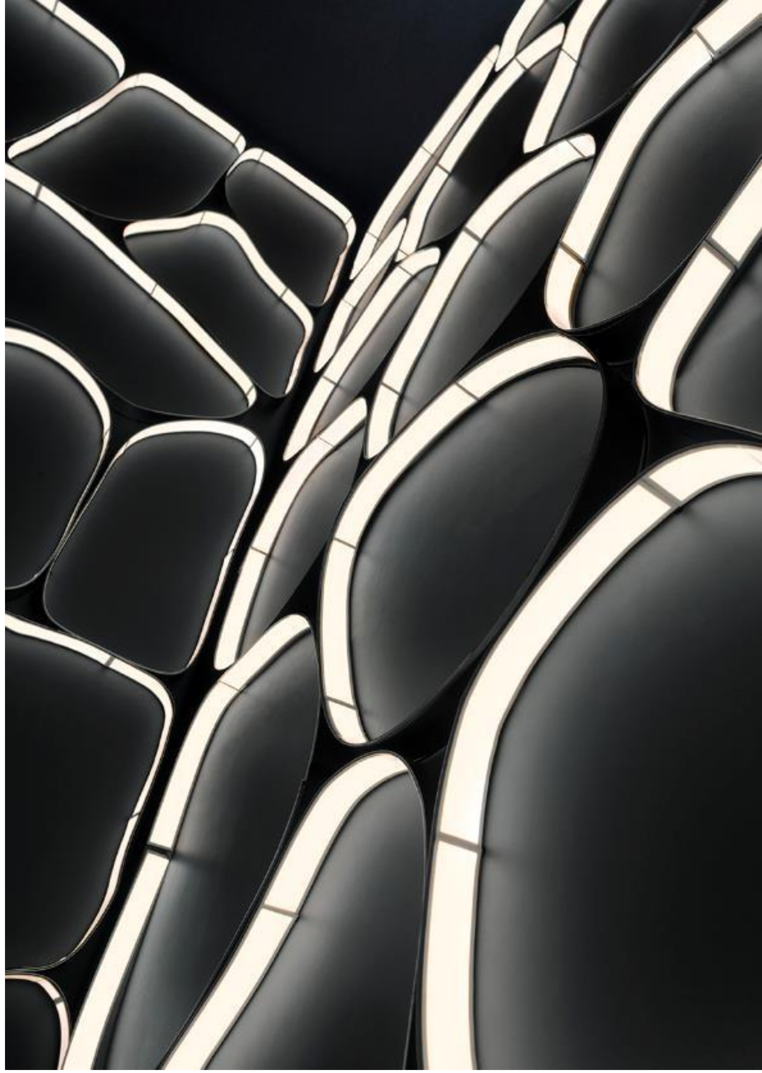
A unique selling point verses LED

Glass and Plastic



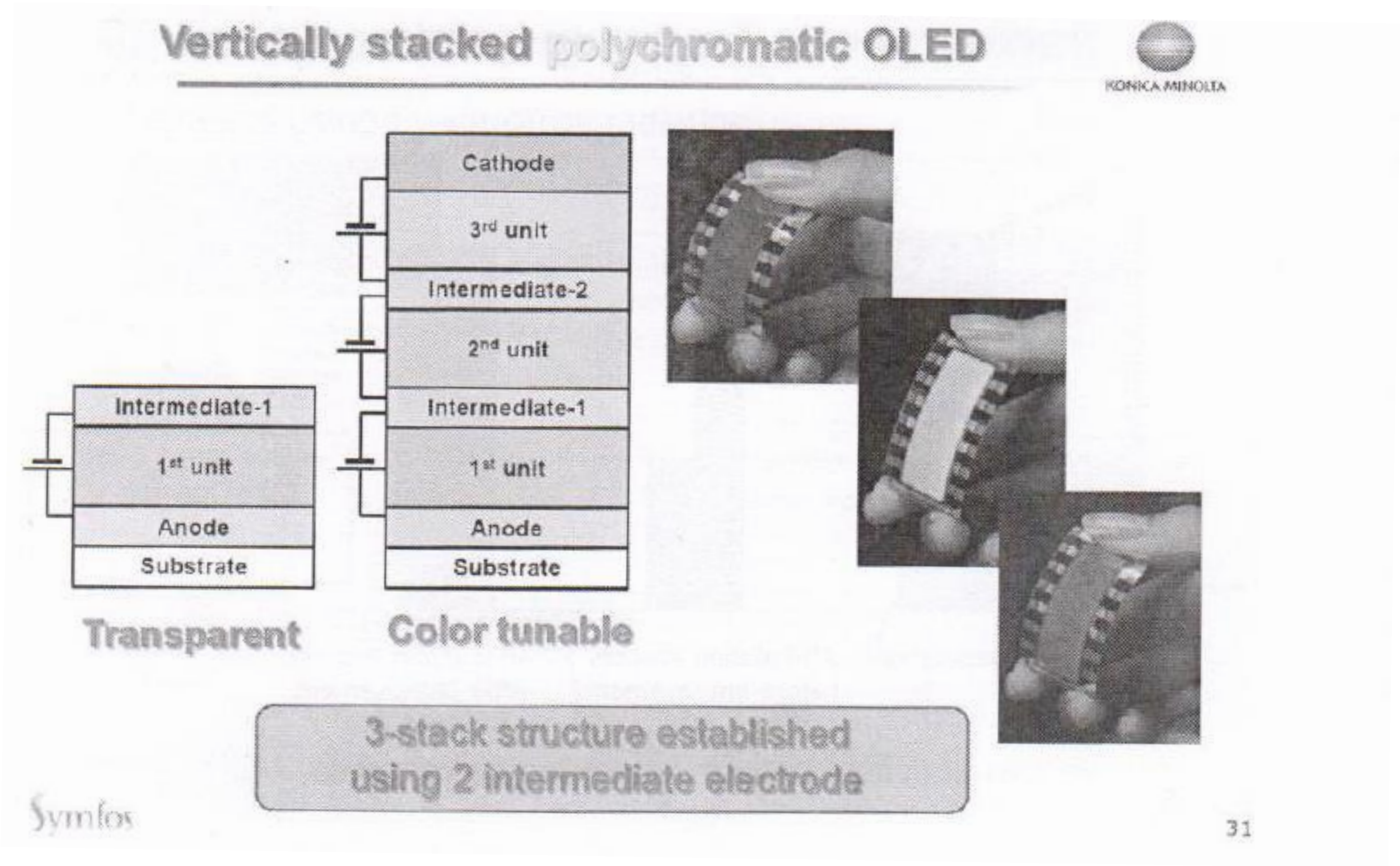
OLEDWorks

LG Display



Blackbody

Grow Demand: Color Changing & CCT Changing



M. Nagato, Konica Minolta 6th Annual China International OLEDs Summit, 2017

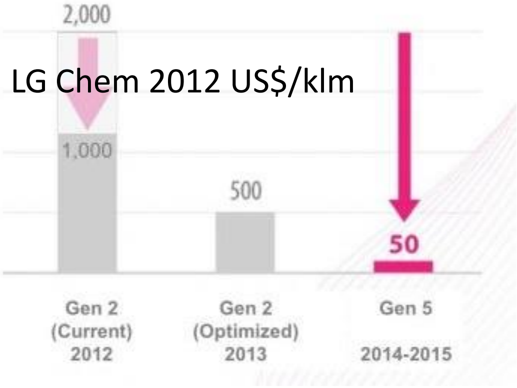
Lower Cost: 2 Steps

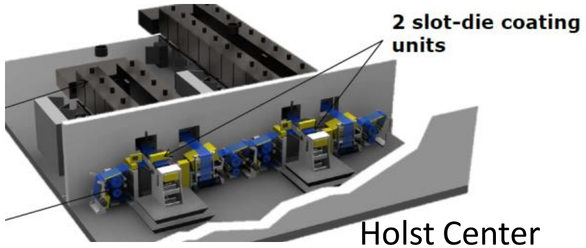
- The next step in cost-down will be G5 sheet-cut machines (LG is building this machine now)
  - On-line in Asia in 2017, North America in 201x?
- The step after this will be R2R processing for further cost down
  - Corning estimated R2R processing will reduce the cost of OLED lighting by 30%
  - This make more sense then going to G8 – diverging from the display model.

Lower Cost: Current Flexible OLED Programs in Asia and Europe

- LGD announces G5 production line ($185M)
  - Previously predicted to give 10x cost down.
- Pi-Scale Project in Europe for R2R with 14 partners (~$16M gov't funding)
- ITRI in Taiwan working on OLED lighting with R2R
- GJM of Korea develops R2R OLED equipment
- Konica Minolta – starting their G5 R2R machine (capacity of 1 million panels/month)

LG Chem 2012 US$/klm





Holst Center

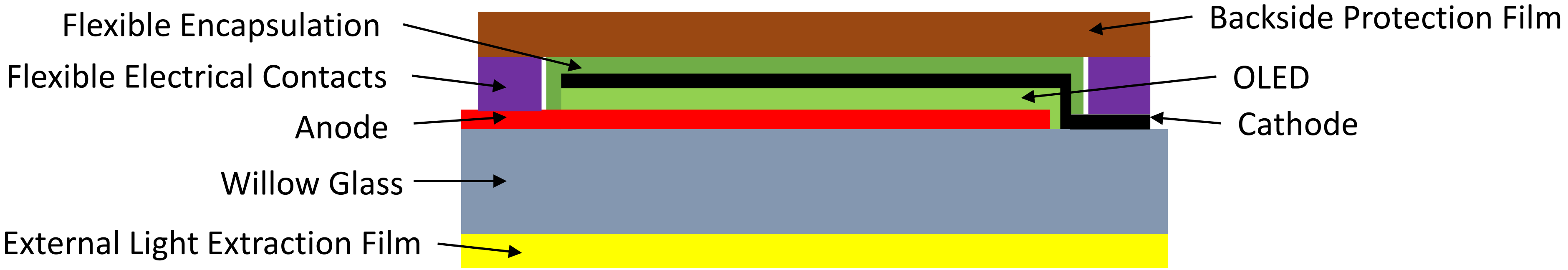
GJM of Korea – R2R OLED equipment

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



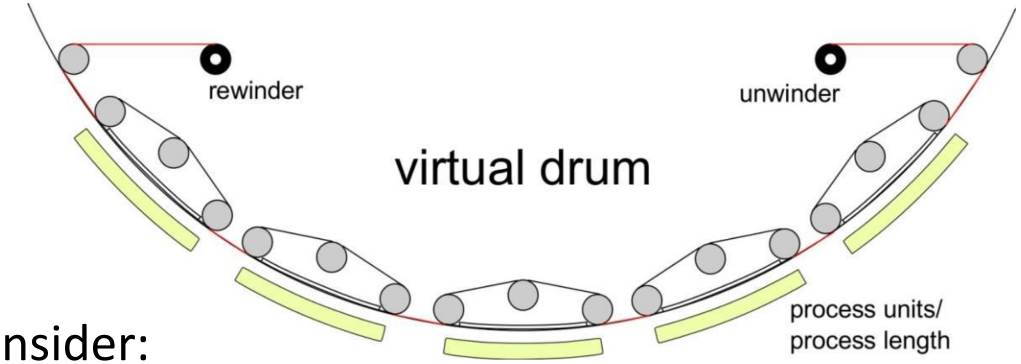
- Careful engineering and design required to make the OLED product robust to handling
  - Selection of materials and thicknesses is critical to control stress and strain in each layer
    - The design of the location of neutral axis during bending is important
- Protection of glass surfaces and glass 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.

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 in Phase IV
    - 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.

Web Handling and Web Transport

- Web path length based on today's products:
  - 40 organic layers, 0.5m per layer, + cathode = 25 m



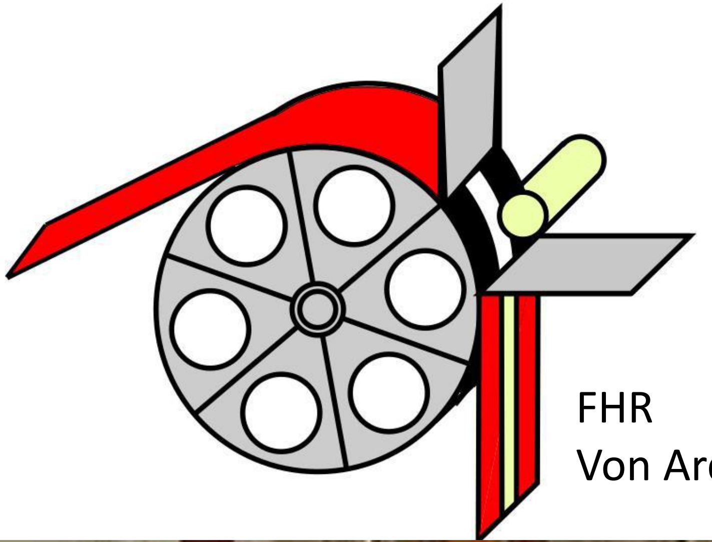
The "virtual" bottom of a drum the size of a Ferris wheel

FHR Transport ideas

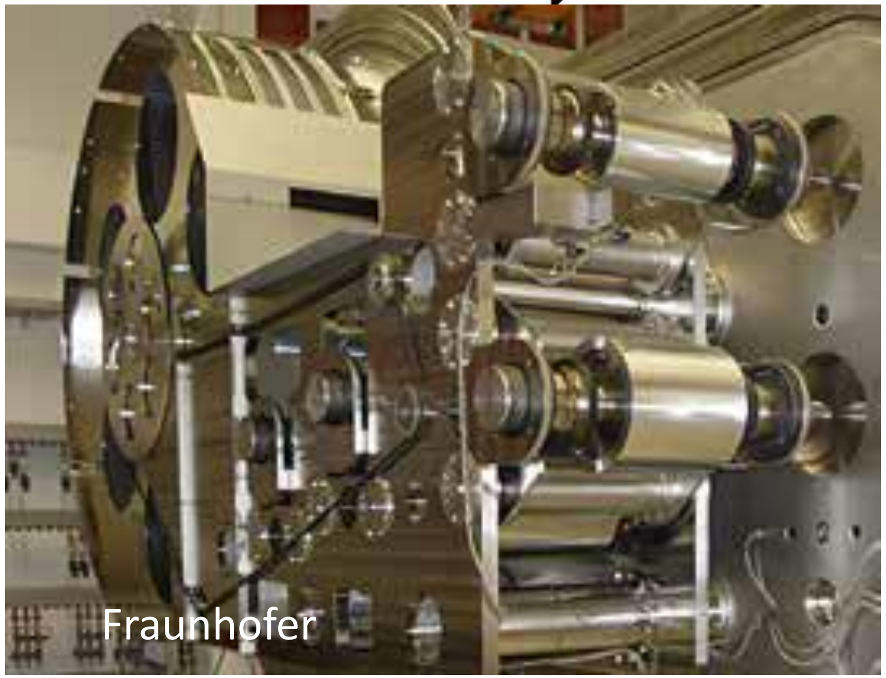
- Issues to consider:
  - Web tension for a long web path – **substrate stretch, breaking fragile layers, web steering (vs scraping on edge-guide)**
  - Should we consider web support with narrow front-side wheels or transverse tension
  - All moving contact generates particles
- Today we do deposition up in all lighting machines to control particles on the substrate.
  - Should we consider depo down and understand how to control particles?
- We need to get the web into and out of vacuum without damage.

Masking Option #1 – Stripe Masks

- Stationary stripe masks held in very close proximity to the substrate – used at Fraunhofer
- Difficult to adjust from one product size to another
- These stationary masks does not keep the OLED from the transverse areas.



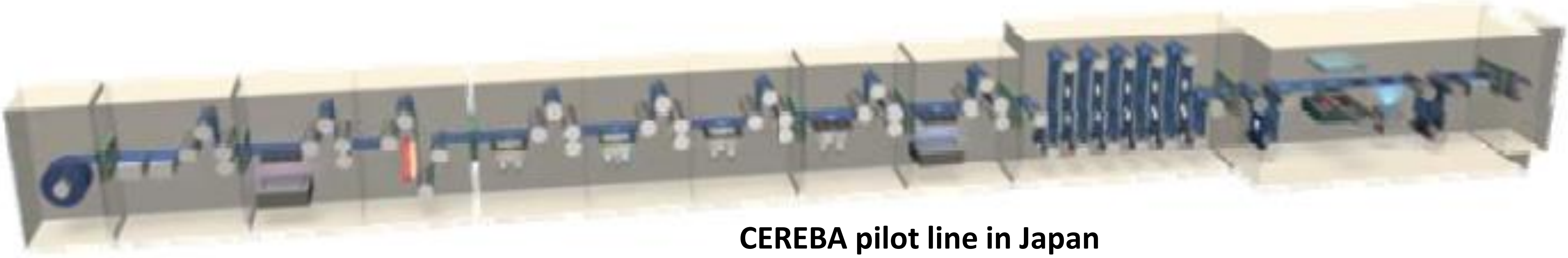
FHR
Von Ardenne



Fraunhofer

Fraunhofer

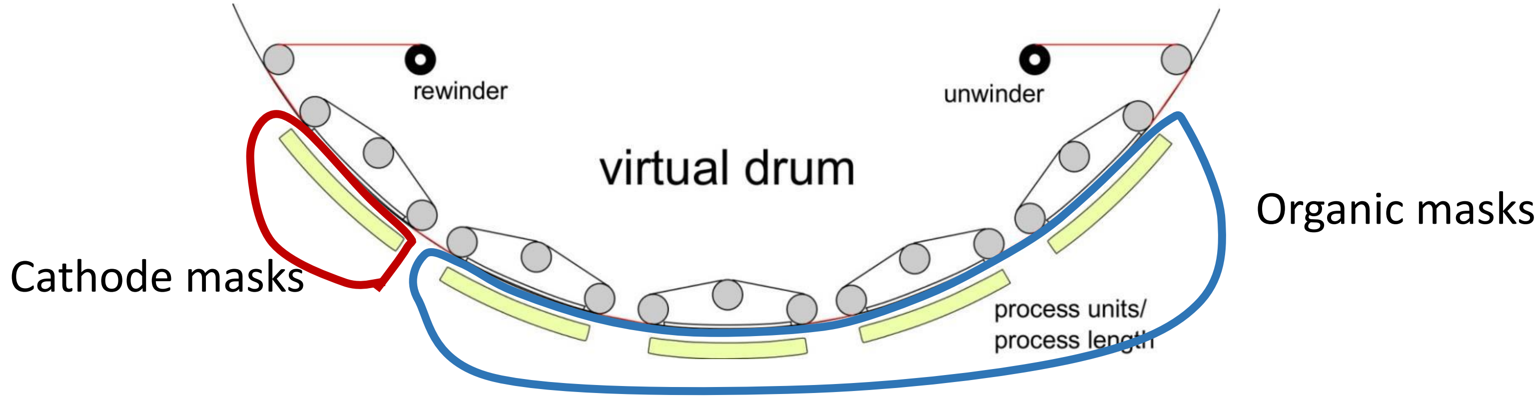
Masking Option #2 – "Stop and Stare" Deposition



CEREBA pilot line in Japan

- Requires area evaporation sources
  - Uniformity challenges for large 2D areas for large web widths
- Requires web position-adjustment between stations
  - Shown above has front-side web contact
- Low productivity
  - High speed transport between depositions generates particles

Masking Option #3 – Flying Masks



- Make a belt of masks that recirculates below the sources
- Match the speed of the masks to the substrate
- Align on the fly
- Clamp, deposit organics, unclamp (PARTICLES!)
- Repeat for Cathode
- Very difficult to change masks for different product designs

Summary

- Solid State Lighting is the future and OLED will be a significant part
- OLED performance is good and improving rapidly
- Performance gap with LED is shrinking
- Price is dropping and volume is growing
- Grow demand with panel and integration level variety, flexible and bendable panels and color changing panels
- We will achieve lower cost with high capacity machines
- R2R will enable both lower-cost and bendable/flexible products