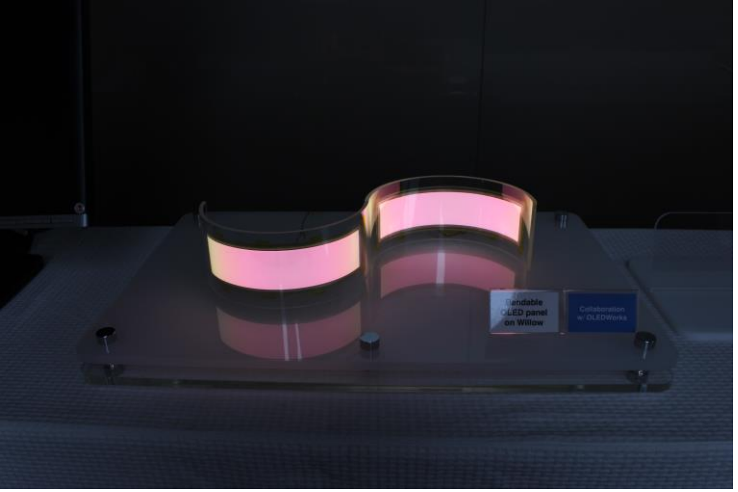
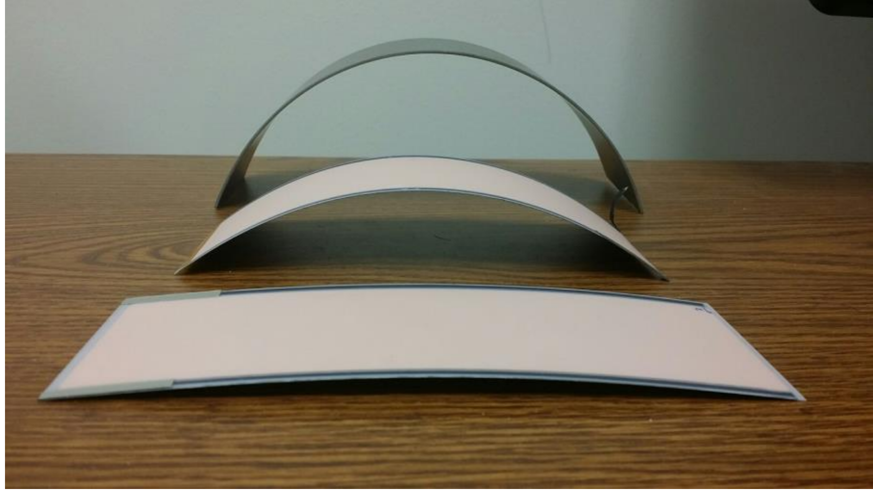




OLED Lighting Production on Thin Glass

The perspective of an OLED lighting manufacturer

John W. Hamer and Wolfgang Doetter

OLEDWorks

Outline

- Introduction to OLEDWorks
- Motivation for OLED lighting on thin glass
- Bendable OLED lighting panel product properties and requirements
- OLED manufacturing processes
  - From pilot production to mass production
- Key processes for further development
  - Substrate Web Handling and Transport
  - Masking for OLED deposition
- Summary

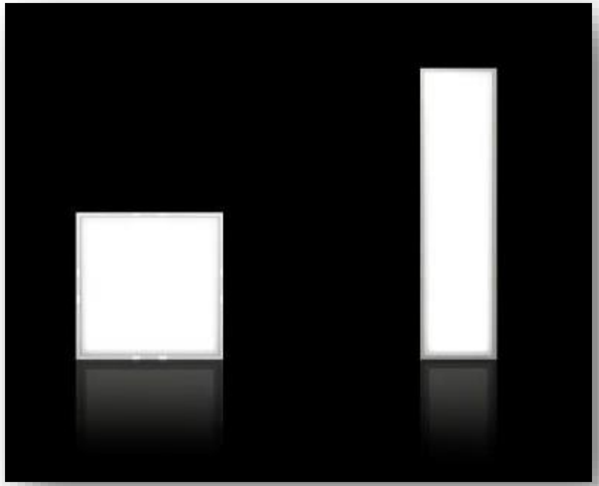

Acuity Brands Ltd

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

DOE Gateway / NYSERDA Demonstration

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

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

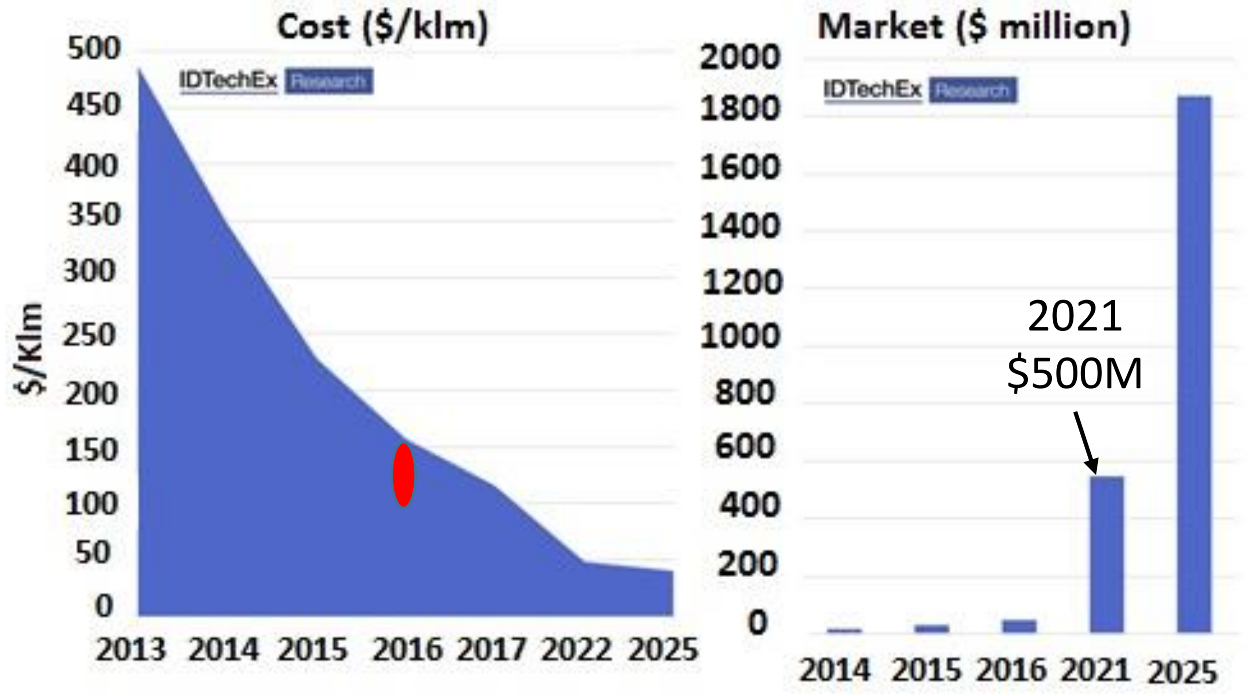

DOE Gateway in Rochester NY

OLEDWorks
Naturally Illuminating

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.

Prediction of Panel Prices and Volumes



OLED panel prices and market - IDTechEx made these predictions in 2013, and the prediction were unchanged in 2016

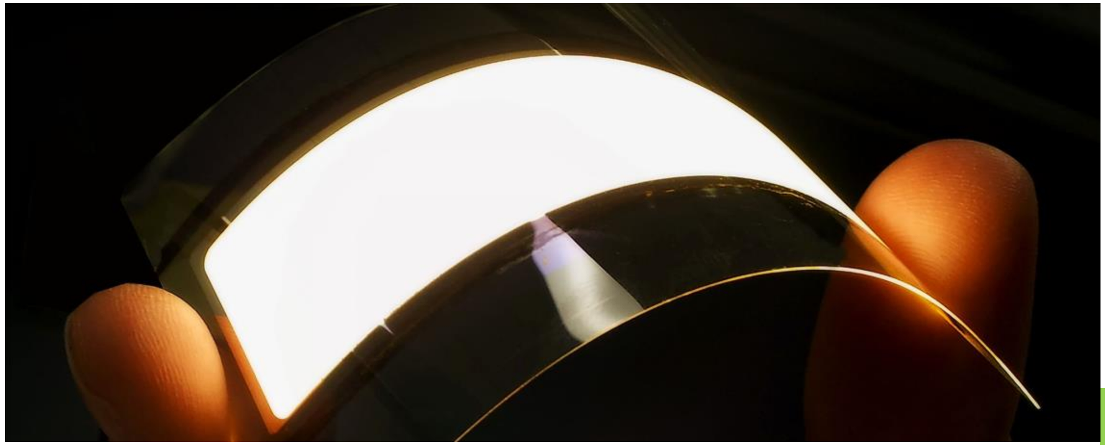
For panel prices – the industry appears to be a bit ahead of the curve – the red ellipse.

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

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

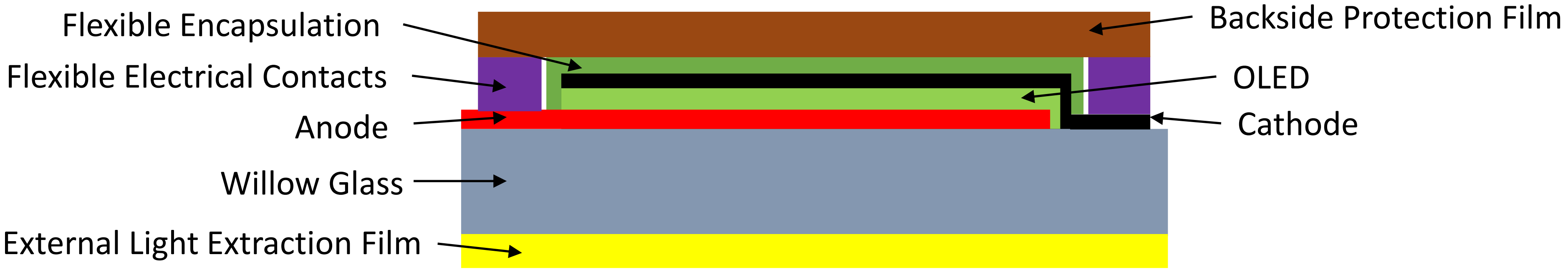
Market request is to match rigid technology platforms in price performance while additionally offer USP's bendable OLED's

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

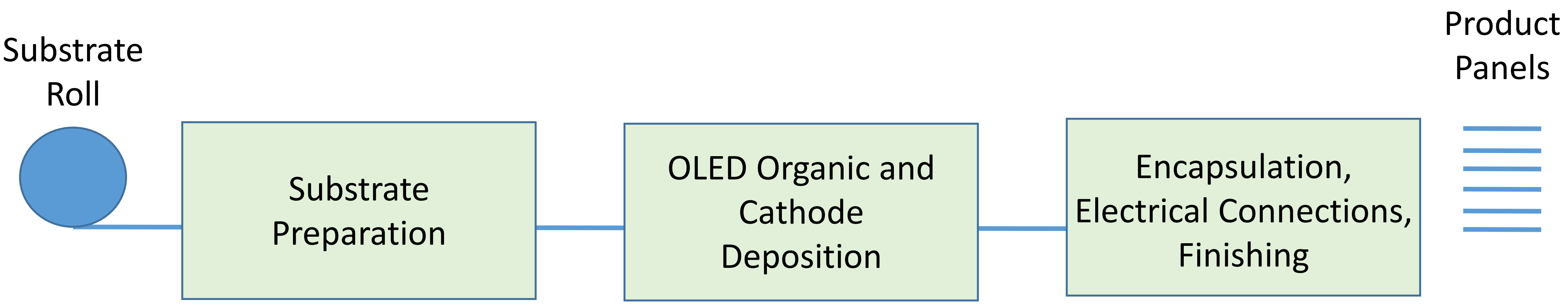


- Careful engineering and design required to make the OLED product robust to handling
  - Selection of materials and thicknesses is critical to control stress and strain in each layer
    - The design of the location of neutral axis during bending is important
- Protection of glass surfaces and glass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

OLED Processing Costs: R2R Needed for Ultimate Low-Cost Production

1. As volumes increase, OLED lighting industry will have cost reduction due to economies of scale over today's pilot machines
2. Major cost-down advantages will occur when we get to G5 Sheet-to-sheet machines
    1. LG machine will be in production in Asia in 2017-18
    2. North America or Europe in 201x?
3. 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.

Processing of OLED Lighting Panels on Thin Glass



- The following slides are a summary showing a possible progression in equipment and processes
  - From a simple start using existing equipment
  - To a high-throughput ultimate line for low-cost product
- Many variations in this progression are possible

Process Flow for Thin Glass: Final Target –from roll of glass to panels

Substrate in roll → Depo internal LE → Depo anode and pattern → Depo insulating layers → Cleaning, drying, pretreat

Transfer web in high vacuum → Org mask alignment → OLED deposition → Transfer to cathode mask → Cathode Deposition → Transfer web out of hi vacuum

Encapsulation → Cutting into pieces → Electrical connection → Lamination of external LE → Testing

Legend

- Roll or web outside vacuum
- Roll or web inside high vacuum
- Sheets or pieces in vacuum
- Sheets or pieces out of vacuum

Phase I – Rigid Carrier-Glass for all Steps

Substrate in roll → Cutting into sheets → Bond onto rigid carrier glass

Depo internal LE → Depo anode and pattern → Depo insulating layers → Cleaning, drying, pretreat

Transfer Into high vacuum → Org mask alignment → OLED deposition → Transfer to cathode mask → Cathode Deposition → Transfer out of high vacuum

Encapsulation → Debond carrier and cut pieces → Electrical connection → Lamination of external LE → Testing

Phase I – Rigid Carrier-Glass for all Steps

Advantages

- For many steps, this runs on the current high volume rigid OLED manufacturing platform.
- Lower cost to learn about handling flexible substrates
- Fastest way to commercialize a first product to start market awareness and interest.

Disadvantages and Challenges

- Product is expensive due to carrier glass - wasted
- Requires and investment in bond and debond technology development and process equipment that are not part of final process
- Some process changes are necessary for thin-glass on carrier.

Phase II – Front-End Processes Done R2R

Substrate in roll → Depo internal LE → Depo anode and pattern → Depo insulating layers → Cutting into sheets

Bond onto rigid carrier glass → Cleaning, drying, pretreat

Transfer Into high vacuum → Org mask alignment → OLED deposition → Transfer to cathode mask → Cathode Deposition → Transfer out of high vacuum

Encapsulation → Debond carrier and cut pieces → Electrical connection → Lamination of external LE → Testing

Phase II – Front End Processes Done R2R

Advantages

- Converts the front-end processes to R2R first – to reduce substrate cost (e.g. FOSA LabX 330)
- These processes are highest volume easiest to convert to R2R.
  - One front-end line could supply product to many machines at different phases.
- Uses existing OLED equipment

Disadvantages and Challenges

- Expensive product due to carrier glass
- Requires and investment in bond and debond technology development and process equipment that is not part of final process

Phase III – Thin glass supported on masks and frames

Substrate in roll → Depo internal LE → Depo anode and pattern → Depo insulating layers → Cleaning, drying, pretreat → Cutting into sheets

Clean particles from sheet → Put sheets on mask in frame

Org mask alignment → Transfer Into high vacuum → OLED deposition → Transfer to cathode mask/align → Cathode Deposition → Transfer out of high vacuum

Encapsulation → Cutting into pieces → Electrical connection → Lamination of external LE → Testing

Phase III – Thin glass supported on masks and frames

Advantages

- Existing rigid glass pilot machines can be used with modification for
  - Feeding frames in and out of vacuum
  - Robot to move glass between frames in vacuum
- Elimination of expensive carrier glass and debonding operations
- Able to continue to use cluster-type TFE after thin-glass flip onto support.

Disadvantages and Challenges

- Need control particles generated during cutting roll into sheets (e.g. MDI CO2 laser system)
- Load-lock in carriers (usually carriers remain in vacuum)
- Transfer to cathode mask in vacuum

Phase IV – R2R inside vacuum, reroll before passivation and encapsulation.

Substrate in roll → Depo internal LE → Depo anode and pattern → Depo insulating layers → Cleaning, drying, pretreat → Wind roll

Unwind roll and splice → Transfer web to hi vacuum → Org mask alignment → OLED deposition → Cathode mask alignment → Cathode deposition

Transfer web out of hi vacuum → Wind roll and cut

Unwind roll

Encapsulation → Cutting into pieces → Electrical connection → Lamination of external LE → Testing

Phase IV – R2R inside vacuum, reroll before passivation and encapsulation

Advantages

- Suitable for large-generation continuous in-line machine
- Front-end, OLED depo, and encap section are all R2R but autonomous for higher uptime and yield.

Disadvantages and Challenges

- Web into and out of vacuum – differential pumped sections
- Transverse masking is a major challenge without particle generation
- Transport of glass without breaking (tension, steering, control) is a major challenge
- Wind up before encapsulation without particle and contact damage

Phase V – R2R continuously through OLED deposition, passivation, and encapsulation.

Substrate in roll → Depo internal LE → Depo anode and pattern → Depo insulating layers → Cleaning, drying, pretreat → Wind roll

Unwind roll and splice → Transfer web to hi vacuum → Org mask alignment → OLED deposition → Cathode mask alignment → Cathode deposition

Transfer web out of hi vacuum

Encapsulation → Cutting into pieces → Electrical connection → Lamination of external LE → Testing

Phase V – R2R continuously through OLED deposition, passivation, and encapsulation.

Advantages

- No roll after OLED – less chance of particle damage
- No rolling up of substrate after unrolling thin glass stock for higher yield.
- No inventory of WIP

Disadvantages and Challenges

- All operations are in-line and synchronized – concern about uptime and yield.
  - Cannot sample rolls before encap to save cost of encap for out-of-spec product.
- All TAC times must be matched.
- Process changes are difficult
- Product changes are difficult

Development Tasks and Goals

	Phase I – Rigid carrier-glass for all Steps	**Phase II – Front-end processes done R2R**	**Phase III – Thin glass supported on masks and frames**	**Phase IV -- R2R inside vacuum, reroll before passivation and encapsulation**	**Phase V – R2R continuously through OLED depo, passivation, and encap**
Major Development Tasks (sorted by amount of development work)	Strengthen glass - Robust panels	Anode pattern continously R2R	Transfer glass in vacuum	**Masking without particles (e.g stripe masks + transverse sides?)**	Longer web path – breakage and particle concerns
	Flex Internal Light Extraction	Isolation layer depo and pattern R2R	Remove particles after cutting	**Web handling (tension, steering) without breakage or particles**	Line startup - quickly with low waste
	Bond/Debond from carrier glass	IEL depo R2R	Load lock in glass on masks in trays	Web feeding into/out of high vac	Product changeover - quickly with low waste
	Flex electrical contact		Thin glass handling for encap	Encapsulation R2R	High levels of equipment uptime required
	Flex encap design and process			Rewind after OLED without particle damage (e.g. Fraunhofer	
Major Goals	Product development	Cost down of substrate	Cost down - no carrier glass	Cost down - organic material usage	Yield up – less particles and damage (no reroll)
	Supply panels for market devel't	Industry supply of rolls of substrate	Build market volume with lower price	Through-put increase - passivation and encap in line	Equipment cost down - no roll handling after OLED

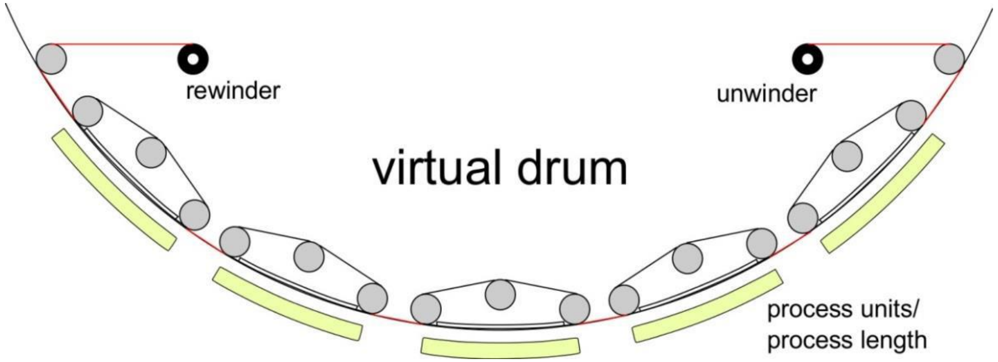
The two boxes in red will be discussed further on the next slides

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



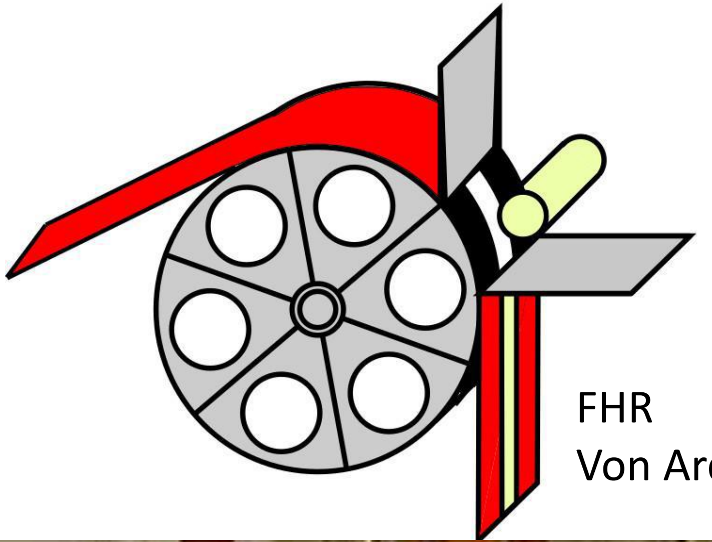
The "virtual" bottom of a drum the size of a Ferris wheel

FHR Transport ideas

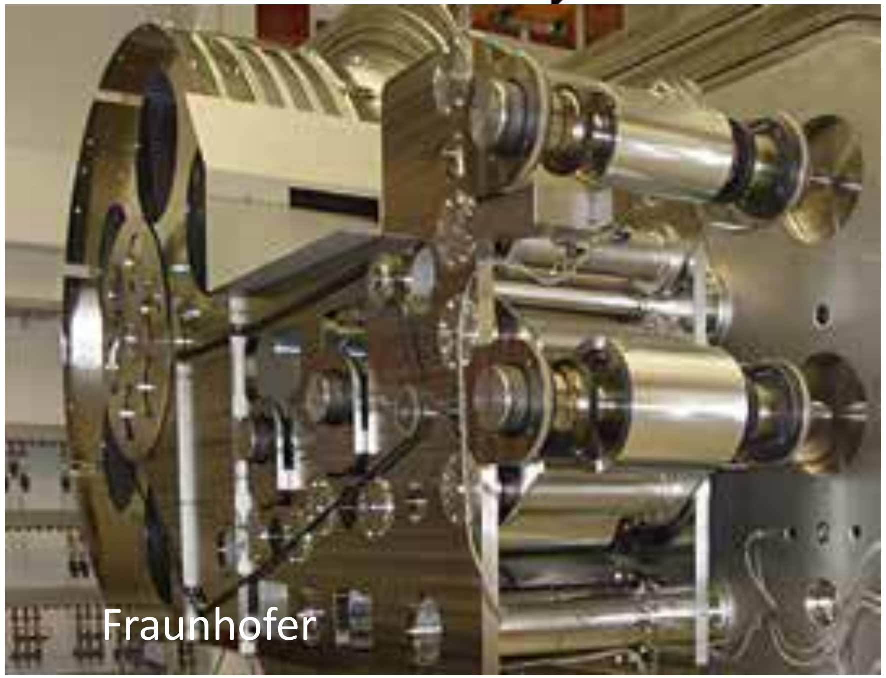
- Issues to consider:
  - Web tension for a long web path – **substrate stretch, breaking fragile layers, web steering (vs scraping on edge-guide)**
  - Should we consider web support with narrow front-side wheels or transverse tension
  - All moving contact generates particles
- Today we do deposition up in all lighting machines to control particles on the substrate.
  - Should we consider depo down and understand how to control particles?
- Can OLED lighting performance by solution printing be ready in time?

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.



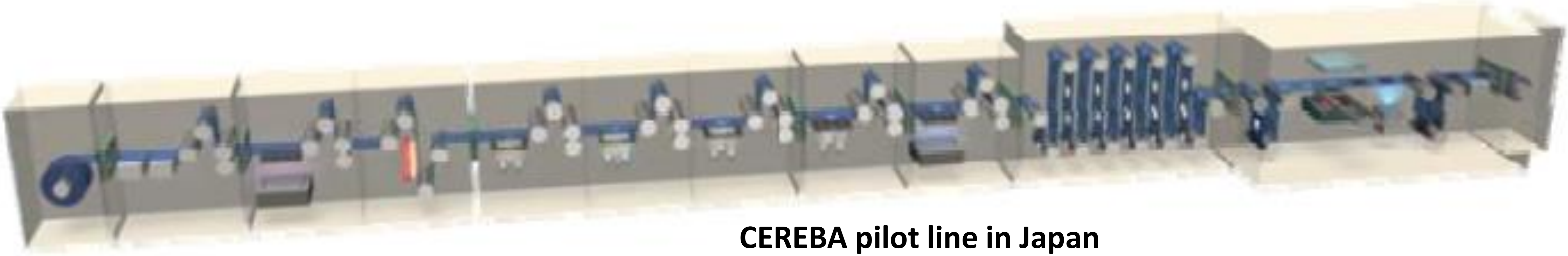
FHR
Von Ardenne



Fraunhofer

Fraunhofer

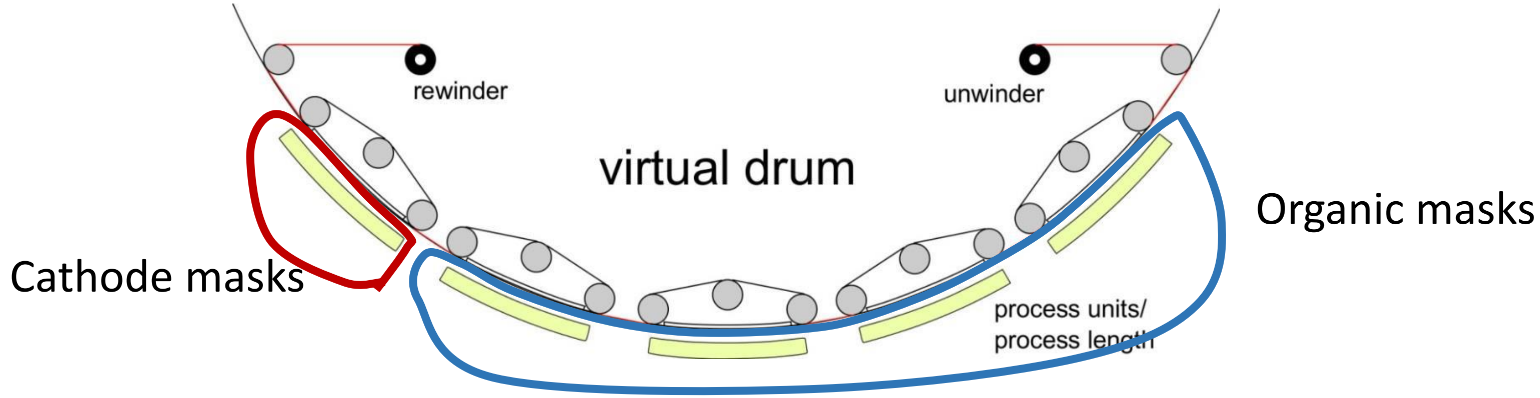
Masking Option #2 – “Stop and Stare” Deposition



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 of it
- The lighting applications where OLED will initially grow will be:
  - Applications close to the user – due to the high light quality, low glare, and low temperature.
  - Applications favoring low volume and weight.
  - Products where design elements affect buying decisions
- The combination of thinness, lightness, and <u>flexibility</u> of OLED will be key differentiators from LED.
- **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.